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# Fundamental Considerations for Preparing Densified Refuse Derived Fuel

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# FUNDAMENTAL CONSIDERATIONS FOR PREPARING DENSIFIED REFUSE DERIVED FUEL

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The bench-scale tests (tests in which the pellets were individually formed), were conducted both to provide data needed for an analysis of the basis dynamics of pellet formation and as an aid in the interpretation of results obtained with the pellet mill. The energy required to overcome die friction was studied independently of the energy consumed in material deformation and compression. By so doing, it became possible to determine the specific effects of die length, diameter, and taper. The results also suggested explanations for the excessive die wear, and for the decreasing energy requirements for increasing the mass throughput observed in commercial pellet mills.


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# FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is a necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved systems technology to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research.

This report presents results of a series of laboratory and pilot scale investigations of the densification of refuse derived fuel. The study objective was to determine the effects of various parameters on the densifications process. The project is one of several projects concerned with using densified refuse derived fuel for energy as an environmentally effective means of disposing of municipal solid waste.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

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## ABSTRACT

A series of pilot-scale tests were conducted to determine the effects of various parameters on the densification of refuse derived fuel (RDF). The experiments included a series of bench-scale experiments involving a single die arrangement, as well as larger-scale studies in which a commercial pellet mill was used.

The bench-scale tests (tests in which the pellets were individually formed), were conducted both to provide data needed for an analysis of the basic dynamics of pellet formation and as an aid in the interpretation of results obtained with the pellet mill. The energy required to overcome die friction was studied independently of the energy consumed in material deformation and compression. By so doing, it became possible to determine the specific effects of die length, diameter, and taper. The results also suggested explanations for the excessive die wear, and for the decreasing energy requirements for increasing the mass throughput observed in commercial pellet mills.

Using data obtained in the tests with the pellet mill, the relationship between specific energy of densification and mass flow rate through a mill was found to be as follows:

$$E_n = a\dot{M}_D^{\,b}$$

where a and b depend upon the die dimensions and characteristics of the feedstock. Other data were developed that relate feed moisture content to resulting pellet density, and feed size to maximum achievable pelletization rate.


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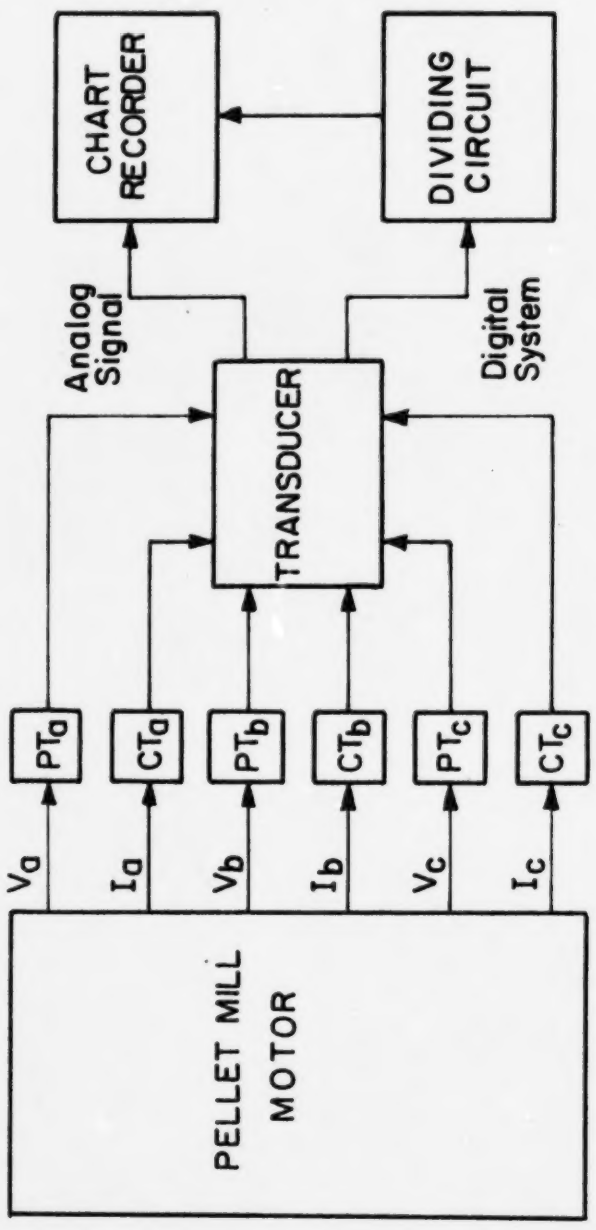


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# Section 1

# INTRODUCTION

## NEED FOR STUDY

Densification imparts to refuse derived fuel (RDF) many attractive features in terms of combustion characteristics, not the least of which are compatibility with other (conventional) fuels in co-firing, and efficiency of transport. A growing awareness of these characteristics is resulting in an expansion of the potential for the utilization of densified RDF (dRDF) as an energy source. However, before this potential can be fully realized, it is essential that an insight into the relatively complex densification process be acquired. The acquisition is made difficult by the fact that machines currently used to produce densified RDF were originally designed to densify materials much different from RDF in nature and composition. Examples of such materials are animal feedstocks and a number of agricultural products. On the other hand, while not being as heterogeneous as the refuse from which it was separated, RDF is far from being a homogeneous material.

An idea of the heterogeneity of RDF may be gleaned from a knowledge of the nature of refuse (municipal solid waste) in general and of the method of producing RDF. Of the mixture of waste that collectively make up refuse, about 75 percent is in the form of non-brittle combustible materials such as mixed paper waste, cardboard, plastics, and putrescibles. The remaining 25 percent, the "brittle" fraction, consists mainly of metals (ferrous and non-ferrous), glass, small amounts of wood, and non-combustible fines. The production of RDF involves a processing of the refuse to separate the brittle materials from the non-brittle combustible materials. The latter make up the RDF. The processing usually is a combination of size reduction, air classification, and screening. An inadequate processing results in an inclusion of varying amounts of non-combustible fines with the RDF. The inclusion not only detracts from the fuel value of the RDF, but also aggravates the problems in the densification process that arise from the heterogeneity of the RDF.

The limited extent of the field experience thus far with the densification of RDF has not been entirely satisfactory. The less than successful record can be blamed on a number of factors, among which the following three stand out: 1) The actual output from a pellet mill typically falls short of its rated output. 2) Dies, rollers, and other moving parts show signs of excessive wear. 3) The machines are difficult to feed and are easily jammed.

## AGRO DENSIFICATION RESEARCH

A first step in the acquisition of an insight into the densification process is a review of the pertinent literature on research and studies conducted by members of the agricultural engineering profession. However, when interpreting results obtained by the agriculturally oriented researchers, it should be remembered that parameters suited to the densifying of agricultural materials may be different from those for densifying RDF. For example, for livestock feedstuffs, pellets of small diameter and low density are preferred. The reason is that it is easier for livestock to eat small, "soft" pellets than large, firm pellets. On the other hand, in densifying RDF, the aim is to produce large and relatively dense pellets.

During the past decade, researchers in the agricultural feed industry have been concerned with expanding their understanding of the nature of the densification process in the hope of improving the process with respect to the densification of agricultural materials such as hay, straw, and alfalfa. The scope of their investigations included both the machine and the material to be densified. In the course of their investigations, they systematically experimented with different feed materials and studied the effect of binders and moisture content. Furthermore, the effects of temperature of material, die geometry, extrusion rate, and pressure all were studied; and power consumption and wear received their due attention. In addition, factors affecting the durability of the pellets were explored. In the conduct of the tests, single-die experimental devices as well as full-size commercial machines were used.

In the early to mid 1960's, Bellinger and McColly [1] and Pfost [2] conducted several studies, some of which were concerned with energy consumption in the pelletizing of hay, while others dealt with the effect of lignin binders, with the effect of die thickness, and with the influence of temperature on the pelletizing process. The researchers evaluated the durability of pellets by means of the tumbling test. In their report [1], Bellinger and McColly refer to data obtained by Butler, which indicated that the energy required to produce an 80-gram pellet of hay (input hay, 12 percent moisture content) by means of a 2.4 in. diameter die at 5000 psi was about 3.7 hp-hr/ton. On the other hand, in his studies Richey noted that an additional input of 11.6 hp-hr/ton over and above that reported by Butler was required. An attempt to reconcile this difference led to research by Bellinger and McColly. They found that as the pressure was increased from 1800 to 3400 psi at a moisture content of 17 percent, the energy requirement increased from 219 hp-hr/ton to 4.08 hp-hr/ton. Pellet density in all cases was 33 $lbs/ft^3$. Their data indicate that doubling the pressure resulted in only a 4 $lb/ft^3$ increase in pellet density, and yet required a factor of about 1.4 additional energy. From the preceding results and observations, a definite relationship between energy and moisture content becomes apparent in that the energy requirement decreases with increase in moisture content. This trend prevailed at both 1800 psi and 3400 psi. (Interestingly, this same trend occurs in the densification of RDF.) The researchers offered no explanation for the relationship.

Results reported by Pfost [2] are compatible with those described by Bellinger and McColly [1]. Pfost reviewed the use of pellet binders by various manufacturers to increase the durability of the pellets. He also evaluated various types of dies as well as methods of conditioning. Pfost worked four different feed materials, two of which had significantly different constituents. The first material, turkey pre-starter feed, contained approximately 44 percent soybean oil meal, 15 percent ground milo, 14.6 percent ground corn, and an assortment of other additives. The second material, poultry layer material, contained as much as 32.4 percent ground milo and only 15 percent soybean oil meal. In addition, it had 28 percent ground corn, 5 percent limestone, and various other additives. A difference of importance between the two feedstuffs in the pelletizing process was that between the temperatures reached in the die. With the turkey pre-starter feedstuff, the temperature reached in the die was only 80°F, whereas with the poultry-layer feedstuff it was 125°F. It should be noted that the oil content of the turkey pre-starter was greater than that of the poultry-layer feed. The power required to produce the pellets was 6.5 kWh/ton for the turkey pre-starter, and 4.5 kWh/ton for the poultry-layer feed. The data also showed that the addition of a binder, in this case calcium lignosulphonate, brought about a reduction in power consumption. The durability of the pellet was found to be increased with elevation of temperature increase.

Although intuitively one would conclude that as the power goes up, the density or durability would increase, the data seem to indicate otherwise. In the reported studies, less power was required in the production of the pellets that consisted of material in which the temperature rise was the greater. Furthermore, the resulting pellets were more durable. This anomaly is only apparent, and is simply a reflection of the physics of the densification process, in that the flow of the material through the die and the adhesion and cohesion characteristics would have to change as the temperature rose. Correspondingly, the friction between the material and the die probably decreased, and therefore, less power was consumed.

Another series of tests was performed by Molitoriaz and McColly in 1970 [3], by Waelti and Dobie in 1973 [4], and by Dobie in 1975 [5]. In studies conducted with the use of a rolling compression system, Molitoriaz and McColly developed several empirical relations through which an insight may be gained as to the channel geometry that yields the best results. The two researchers considered different cylindrical and conical types of rollers. They came to the conclusion that the absolute capacity of a roll wafering machine is determined by three factors, namely, the diameter of the wafer, the axial or discharge velocity of the wafer, and the density of the wafer. Optimum diameter is a function of drying rate, structural stability, and handling characteristics of the wafers. The researchers developed relationships between power consumption and density which showed that power consumption increases with increase in density. This relationship is consistent with other findings. An interesting observation in this series of tests dealt with the orientation of the layers in the roll. It was found that the arrangement of wrap layers in a roll wafer has an advantage over a random arrangement of fibers, in that the overlapping layers are bound together by adhesion, cohesion, and an interlocking of the interwoven stems. The power

consumed in the production of wafers having a diameter of 3 to 5 in., a length of 4 to 6 in., a density of 25-30 lbs/ft$^3$, and a moisture content of 20 percent was on the order of 10 hp-hr/ton. Power consumption increased sharply after densities of 40 lbs/ft$^3$ were reached.

Observation made by Waelti and Dobie confirmed the importance of fiber orientation. In their tests, they found that when interlocking occurred between the stems, a durable wafer usually was produced. The two researchers also noticed that the interlocking stems rarely if ever, takes place in commercial machines; because the fibers are arranged in a more or less parallel pattern, with little occasion for interlocking as the densification process proceeds. In his 1975 studies, Dobie used a laboratory hydraulic press that was essentially a single-cube machine. The parameters of the machine were 6000 psi; die temperatures approximately 175°F; and extrusion time, about 6 seconds. Two binding agents were tested; namely GL-50 and PMS. GL-50 is ammonium lignosulfonate; and PMS is a commercial binding agent. According to the results, binder to the extent of 5 percent was needed to produce a cube that would not disintegrate. With the addition of a binder, cube densities on the order of 35 lbs/ft$^3$ could be produced.

## Section 2

## STRUCTURE OF THE STUDY

The study conducted by the authors of this report and described herein involved the development and following of a systematic approach to the gathering of the data needed to gain a deeper insight into the physics of the densification of RDF, i.e. of the so-called "light" fraction of municipal solid waste. The study was carried out by way of two distinct, but interrelated courses of action, one of which was in the form of a series of experiments in which pellets were produced by means of a single die under laboratory conditions. In the other series, a commercial densification machine was used.

The first step in the quantification of the interrelationship between the macroscopic parameters governing the densification process was made by an investigation that involved the pellet mill. In the investigation, feedstock for the mill was prepared by processing municipal solid waste into air classified and screened air classified light fractions that had a variety of size distributions and moisture contents. Throughout the text which follows, "air classified light fraction" and "RDF" are used interchangeably as are "screened air classified lights" and "screened RDF." A series of one-half, three-quarter, and one inch pellets were produced. Measurements were made of the throughput and power consumption and of pellet density and moisture content. With the use of values obtained in the measurements, it was possible to demonstrate correlations between power consumption and throughput, pellet density and moisture content, characteristic particle size and throughput, pellet size and power consumption, and pellet size and throughput. In addition, quantitative observations were made of the relation between die wear and macroscopic parameters.

The single-die experiments were designed to: 1) aid in the interpretation of the pellet mill results; 2) test and evaluate the effects of parameters such as die taper and temperature; 3) gain an insight into the physics of the densification process through an evaluation of the internal pellet structure and of the frictional effects between the pellet and internal die wall; and 4) organize the results in a format which would: a) provide guidance for the rectification of problems encountered in the operation of commercial machines, and b) provide insight into the development of improved equipment. In the experiments, screened RDF (i.e. screened, air classified light fraction) passed through a single die positioned in a standard laboratory tensile (compression) tester. The force required to produce a pellet was measured and recorded during the formation process. With the use of the data thus obtained, standard local compression curves were generated for pellets produced under various conditions of die taper, throughput, material

composition, and temperature. By evaluating the area under the local compression curve, the total work can be determined, i.e. the sum of the work involved in deforming the material and that required to overcome die friction. Furthermore, by pushing a formed pellet through the die by means of a rod, the coefficient of friction between the pellet and the die wall can be determined. The information gathered in the studies was used in the development of analytical models that relate the governing parameters.

Section 3

# PELLET MILL STUDIES

## EQUIPMENT

### Test Facility

The test facility is part of the Mechanical Engineering solid waste processing laboratory located at the Richmond Field Station of the University of California (Berkeley). Initially, the facility was developed to study refuse comminution in a laboratory manner, and yet be on a scale directly comparable to that of a commercial installation. The laboratory was later expanded to permit the conduct of studies dealing with the characterization of other unit processes such as air classification, flat bed and trommel screening, air table separation, ferrous and non-ferrous separation, and densification. The versatility of the laboratory was expanded by the addition of a facility for the recovery of paper pulp from municipal solid waste, and facilities for the evaluation of biological processes such as composting and anaerobic digestion of refuse and sludge. For a more complete description of the laboratory and its facilities, the reader is advised to consult references 6 and 7.

The pellet mill used in the study was a California Pellet Mill, a picture of which is shown in Figure 1. The manufacturer's specifications for the mill are listed in Table 1. Pellets in diameters of 1/2, 3/4, and 1 in. could be produced by interchanging dies. The die and roller assembly are illustrated in Figure 2. During the conduct of the study, the mill was installed in the light fraction processing line. By suitably arranging the conveyor system, the densifier could be fed either with the air classified light fraction or with the screened light fraction.

### Measurement of Power Consumption

Power consumption by the pellet mill was measured by means of a versatile and portable power monitoring apparatus that had been developed and used in previous testings of shredders. The monitoring equipment includes a Scientific Columbus Model DL34-2K5A2-AY-6070 watt/watt hour transducer, a Houston Instruments Model 3000 chart recorder, and a digital dividing circuit Figure 3. The nominal inputs to the transducer are such that transformers are required to reduce the line voltage and current.

The transducer itself has three separate elements and is adaptable to single phase, three phase-three wire, and three phase-four wire systems. Two output signals are provided by the transducer. The first is an analog

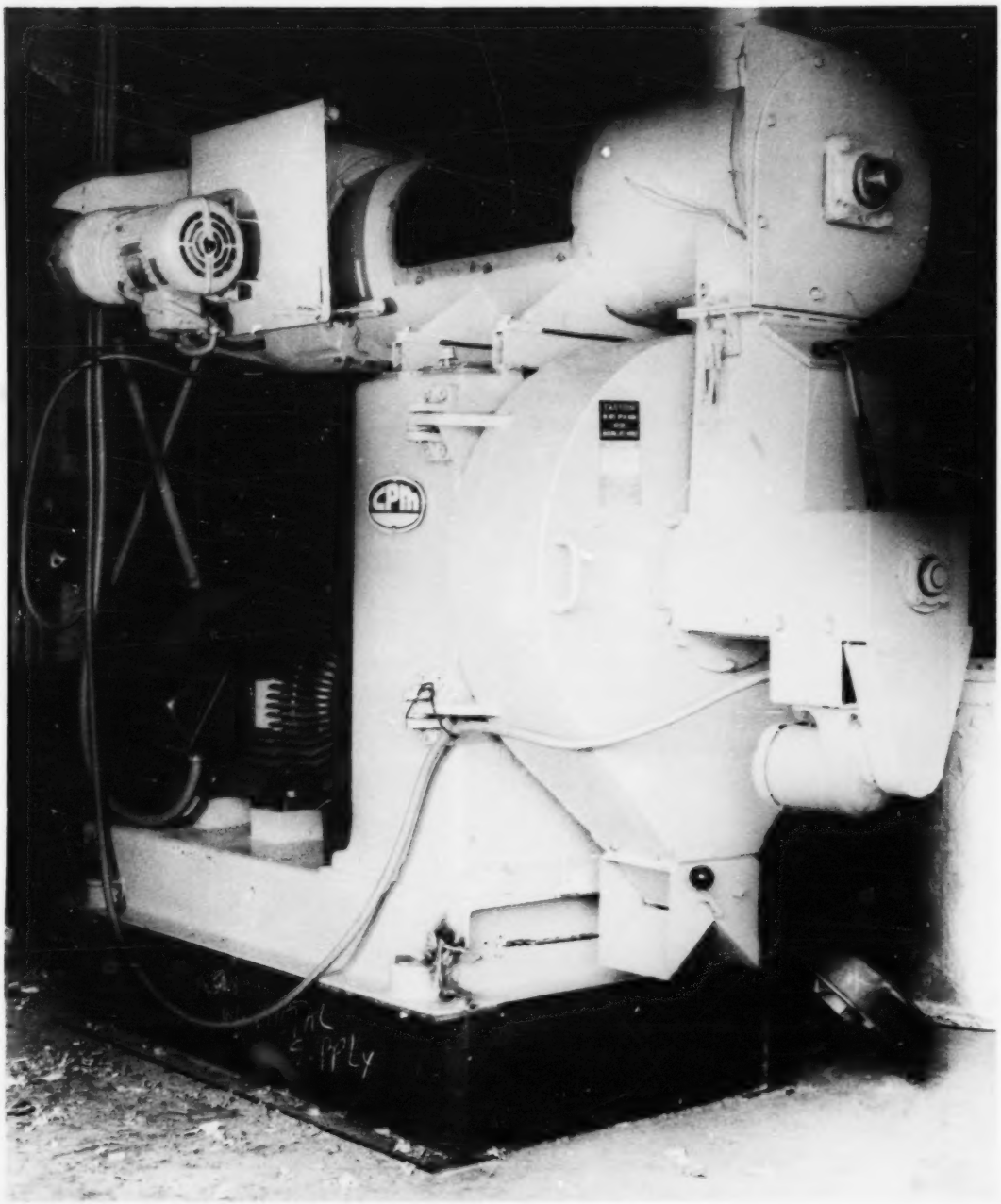

**FIGURE 1: CENTURY PELLET MILL**

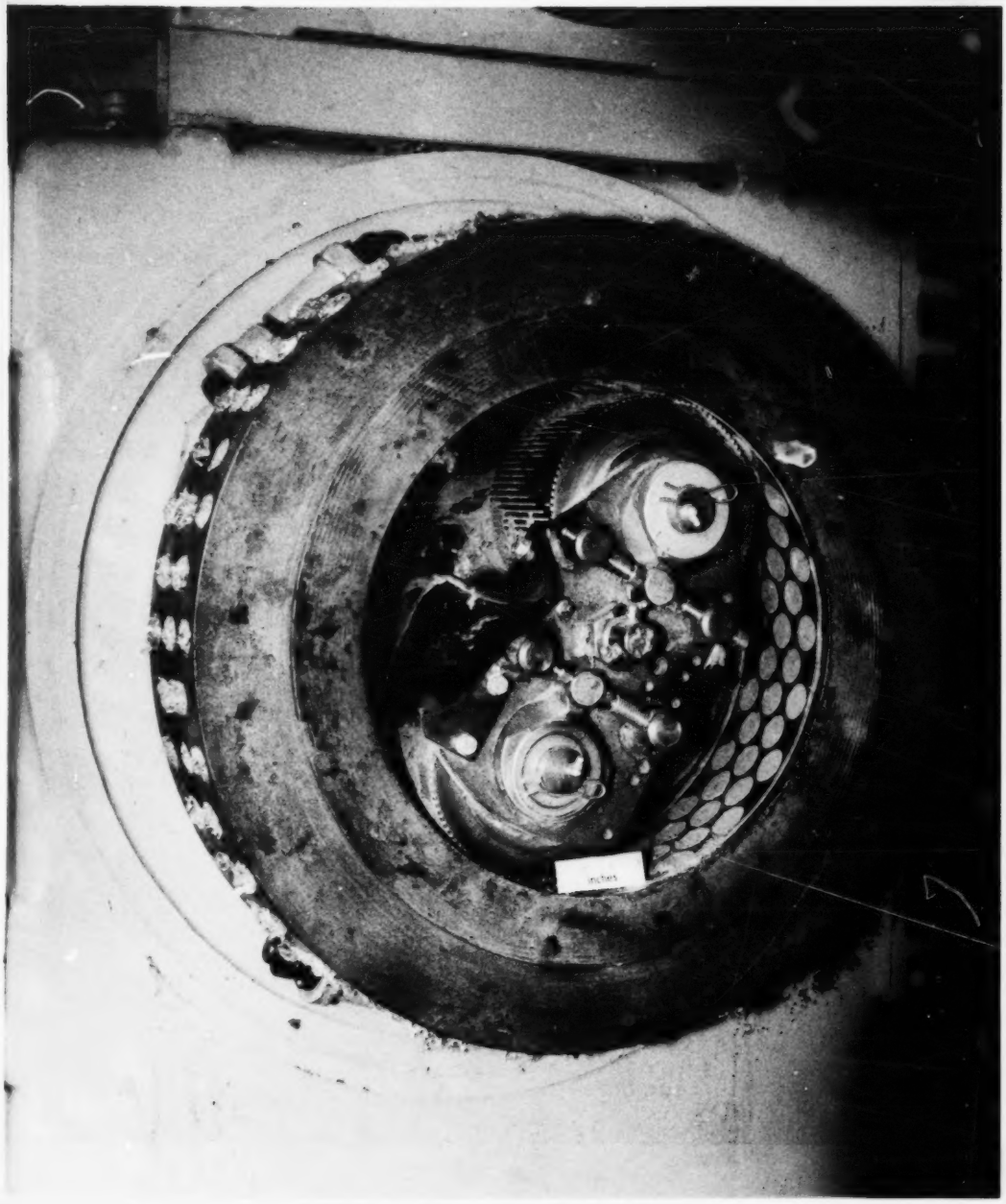

**FIGURE 2: PELLET MILL**
**DIE AND ROLLER ASSEMBLY**

current signal which is directly proportional to power, and may range from zero at no load to one milliamp at full load with all three elements in use.

TABLE 1. PELLET MILL SPECIFICATION

| | |
|---|---|
| Manufacturer: | California Pellet Mill Company |
| Model: | CPM-Century Pellet Mill arrangement kM |
| Power: | 75 hp, 1200 RPM, Reliance motor |
| Dies: | No. 929-16 Alloy steel. Various dimensions specified in text. |
| Rated Capacity: | 2.0 tons per hour |
| Mixer Power: | 3 hp Gearhead motor |
| Feeder Power: | 3/4 hp motor |

The second transducer output is a digital signal directly proportional to the integral of power over time or, in other words, energy. The chart recorder provides a permanent hand copy record of the time history of power and energy. Further details of this system are given in Reference 7.

## FEEDSTOCK MATERIALS

### Preparation

A conventional form of light fraction (i.e. RDF production) was applied in the preparation of the feedstock. The processing began with the delivery of a packer-truck load of municipal solid waste (MSW) to the processing facility. The delivery was made by courtesy of the Richmond Sanitary Service. The MSW was then processed through shredding, air classification, and trommel screening unit operations. A model 48-4 horizontal Gruendler swing hammer mill was used for size reduction. The machine, capable of processing on the order of 10 tons of refuse per hour, is equipped with forty-four 18-kg free-swinging manganese hammers. Power is provided by a 250-hp motor running at 1200 rpm. Product size can be controlled by varying the mill's grate spacings, the range of which is from 0.95 cm to a maximum of 10 cm. Air classification is accomplished by means of a vertical type straight rectangular column device, the capacity of which is about four metric tons per hour. The overall width, depth, and height of the unit are 1.1, 0.9, and 4.6 meters, respectively. The depth of the column can be varied between 0.2 and 0.5 meters inclusively. The average column velocity can be controlled within the range of 0.2 to 0.5 meters per second. The light fraction trommel screen has a capacity of about 2.8 metric tons per hour. Its screen openings are 1.3 cm in diameter. The overall dimensions of the screen are 0.9 meter in diameter and 4.6 meters in length. Its angle of inclination

can be varied between 5° to 20° from the horizontal. Its speed is adjustable within a range of 23 to 38 rpm.

Characteristics

Inasmuch as air classified lights (or RDF) and screened air classified lights (screened RDF) served as the feedstock in the study, their characteristics become those of the feedstock. An important characteristic of the screened and unscreened lights is the size distribution of their components. Among other factors, the size distribution is a function of the moisture content of the raw MSW and of the rate at which the raw MSW is passed through the shredder. That size distributions may be several in number and dimensions is illustrated by the various shapes of the family of curves in Figure 4. Thus, the curves plotted in the figure are based on data obtained in three series of runs. In the first series, the MSW was passed through the shredder at 3 tons/hr; in the second, at 0.5 tons/hr; and in the third, at an undetermined rate. The grate spacing at all throughput rates was one-half inch. According to the curves, the particle size distribution was larger at a throughput of 0.5 tons/hr than it was at 3 tons/hr. In other words, the shredded material becomes coarser as the throughput rate is reduced. This is illustrated by the fact that in general a lower percentage of material passed a given size at the lower throughput. Although the exact throughput of series C was not determined, the size distribution curves are indicative of a processing that approaches the 3 ton/hr throughput. The effect of moisture content on size distribution is less pronounced than that of throughput. The curves in Figure 4 indicate that at a given feed rate, the particle size becomes smaller with increase in moisture content. As with throughput rate, a larger percentage of material passes a given size at the higher moisture content.

The screened light fraction (screened RDF) also was produced from MSW passed through the shredder at 0.5 tons/hr and 3 tons/hr. However, other one-half and one inch grate spacings were tried. The size distributions obtained with the spacings at 0.5 in. are plotted in Figure 5; and those at a 1-in. spacing, Figure 6. Not unexpectedly, the nature of the size distributions are similar to those obtained with the unscreened air classified lights both in terms of effect of throughput rate and of moisture content. The processing was such that the characteristic particle size ($X_0$), i.e. the size at which 66.6 percent of material passes, was on the order of 1.3 to 1.4 cm at a grate spacing of 1.0 in. On the other hand, spread of the $X_0$ of the material processed through the 0.5 in. grate was much wider in that a range of 0.9 cm to 1.8 cm is covered. (The spread with the unscreened lights also was quite wide, namely 0.55 cm to 1.6 cm.)

PROCEDURE

The effect of die configuration and feed material on the net power and specific energy consumption were evaluated. Three dies of different length to diameter ratios were tested: 05. in. by 4.0 in., 0.75 in. by 3.0 in. and 1.0 in. by 5 in. Measurements were made of power consumption, throughput, and pellet density and moisture content. Mill power consumption was determined with the use of the power measuring apparatus described in the section

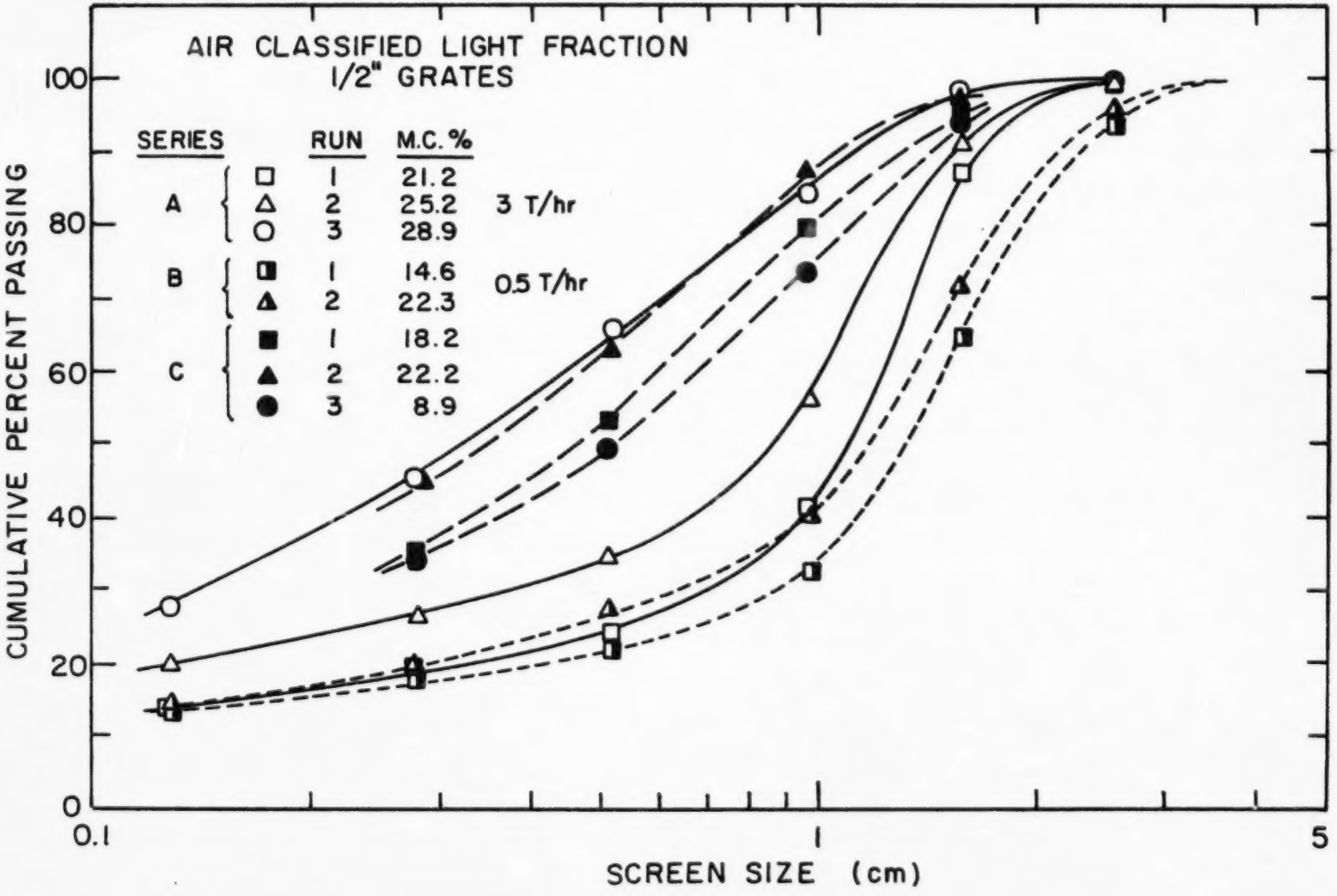


Figure 4 SIZE DISTRIBUTION OF PELLET MILL FEED.

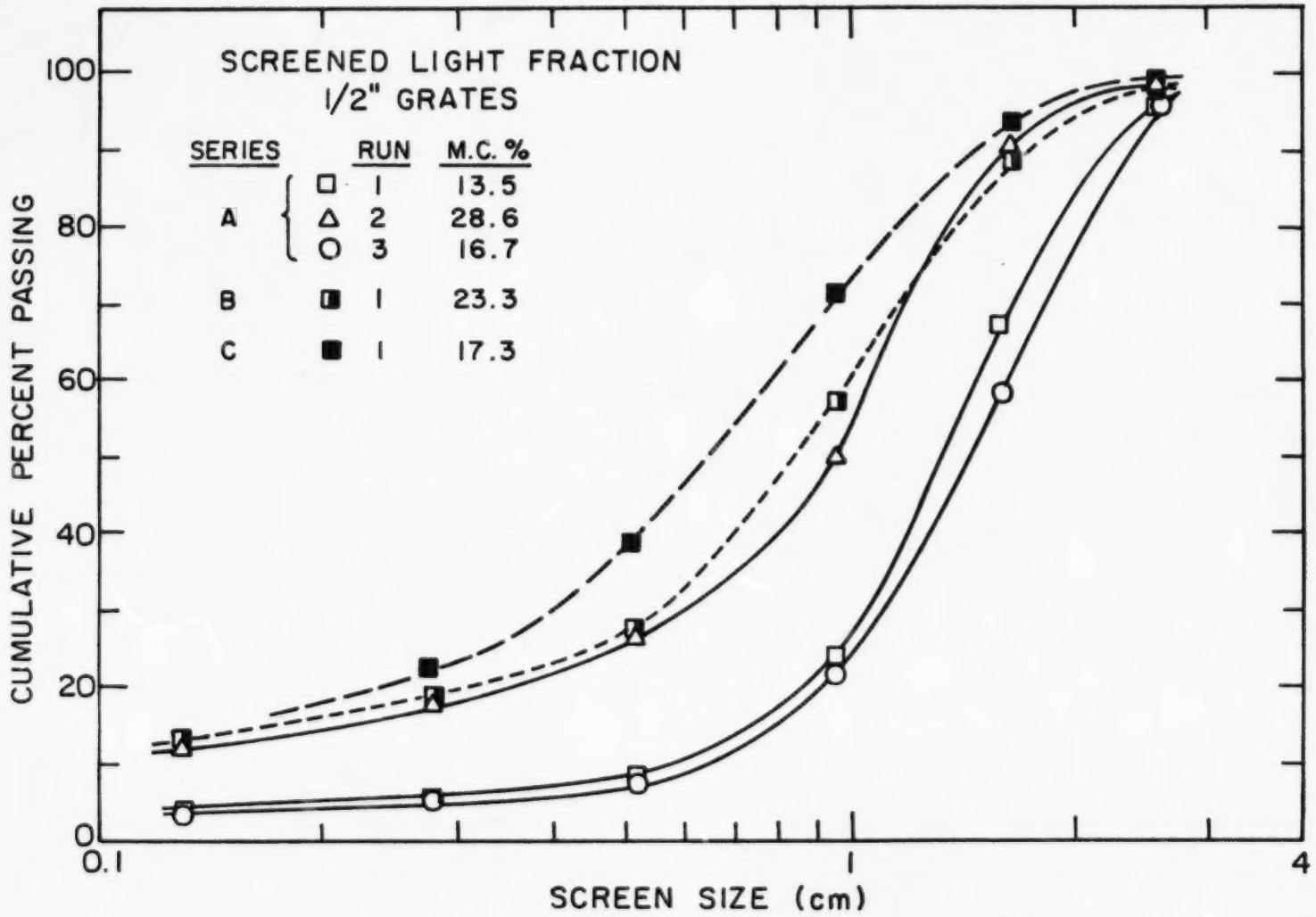


Figure 5 SIZE DISTRIBUTION OF PELLET MILL FEED.

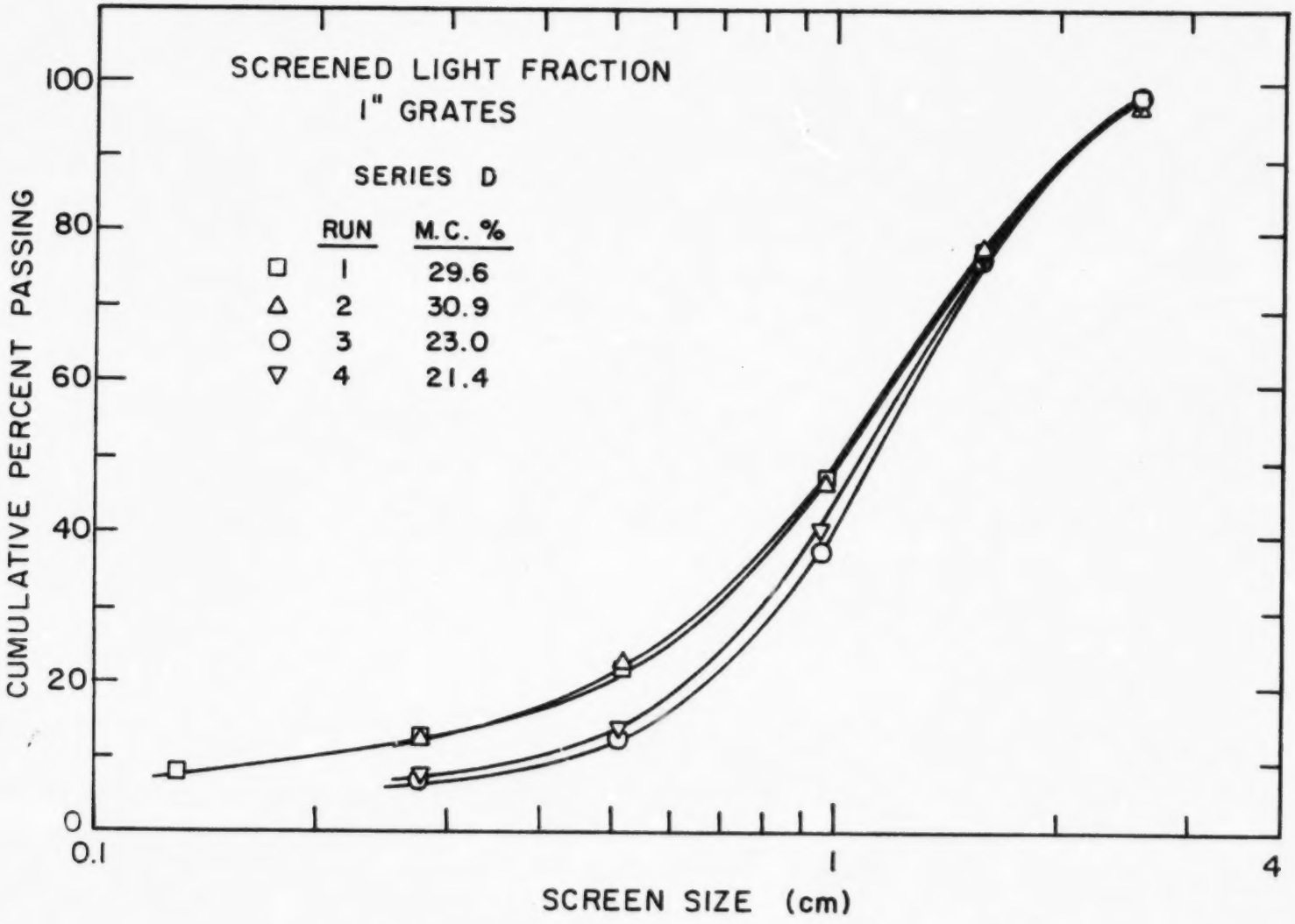


Figure 6 SIZE DISTRIBUTION OF PELLET MILL FEED

"Equipment." Net power consumption was determined by subtracting the freewheeling power of the mill from its gross power consumption. Variations in the mill freewheeling power were duly noted.

By using air classified light fraction and screened light fraction as feed materials, the effects of variations in the composition and characteristic size of the feed material could be evaluated. Thus, the relation between the throughput and the characteristic size of the feed could be considered, and the effect of the feed moisture content on pellet density could be evaluated.

## RESULTS

This section, "Results", is prefaced with a statement to the effect that this series of tests (i.e. with the mill) was intended to be exploratory and not all-conclusive. Initially, the variations in the magnitude of the major parameters had to be determined. Although all permutations and combinations of the variables were not specifically evaluated, a pattern can nevertheless be established from the test data that were collected.

The general nature of the results indicated that net power and net specific energy consumption are a function of the mill throughput. For certain situations, it was found that the basic relationship between energy and throughput was also parametic with pellet density, and in some cases with both pellet density and moisture content.

The mill freewheeling power ranged from 5.4 to 7.5 kW. This variation was related to the particular die being used and to the nature of the contact between the rollers and die. With the mill used in the study, the freewheeling power was on the order of 5 kW with the 1 in. by 5.0 in. die, 6 kW with the 0.75 in. by 3.0 in. die, and 7 kW with the 0.5 in. by 4.0 in. die.

When the screened light fraction had been obtained from MSW shredded with the grate spacing at 0.5 in. and the die ratio was 0.75 in. by 3.0 in., the relation of net power to mill throughput becomes that shown by the curve in Figure 7. The curve is a computation of data for a spectrum of pellet densities ranging from 0.95 to 1.34 g/cc. The nature of the data is such that it cannot be used for rationalizing power with specific values of density.

On the other hand, when correlated in terms of specific energy and throughput, the data become more amenable to detailed analysis. For example, according to the curves plotted in Figure 8, the specific energy data for screened lights processed through the 0.75 in. by 3.0 in. die indicate a discernable dependence upon density. The general orientation of the curves is such that they become steep at higher values of density. In attempts made to describe the curves analytically in terms of either exponential or power law relations, it was found that a power law relation of the type

$$E_n = a\dot{M}_D^{\,b}$$

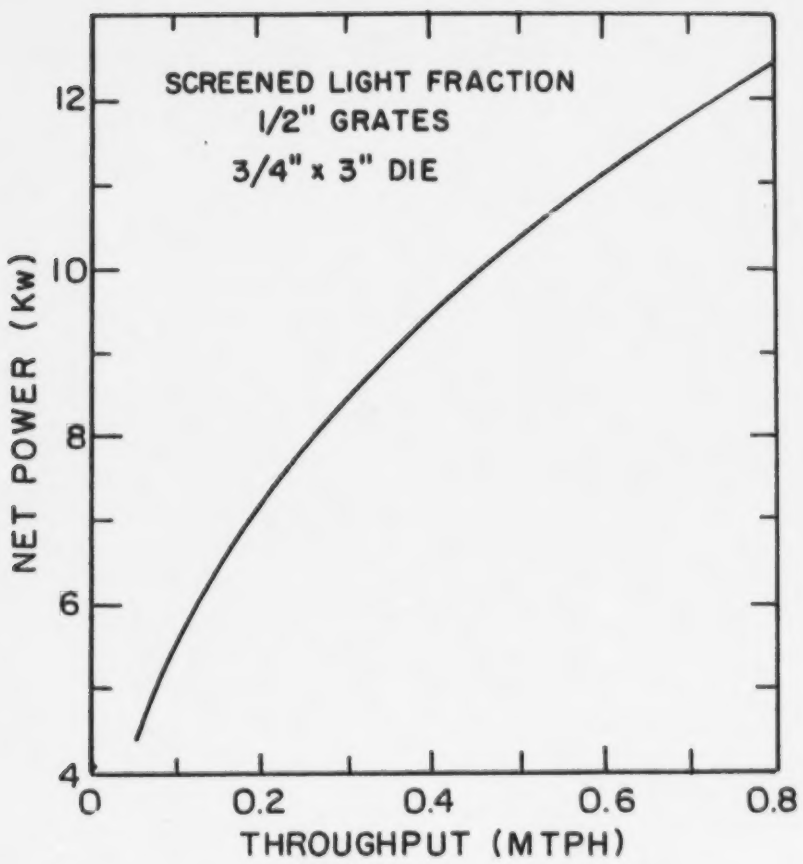


Figure 7 POWER VS. THROUGHPUT

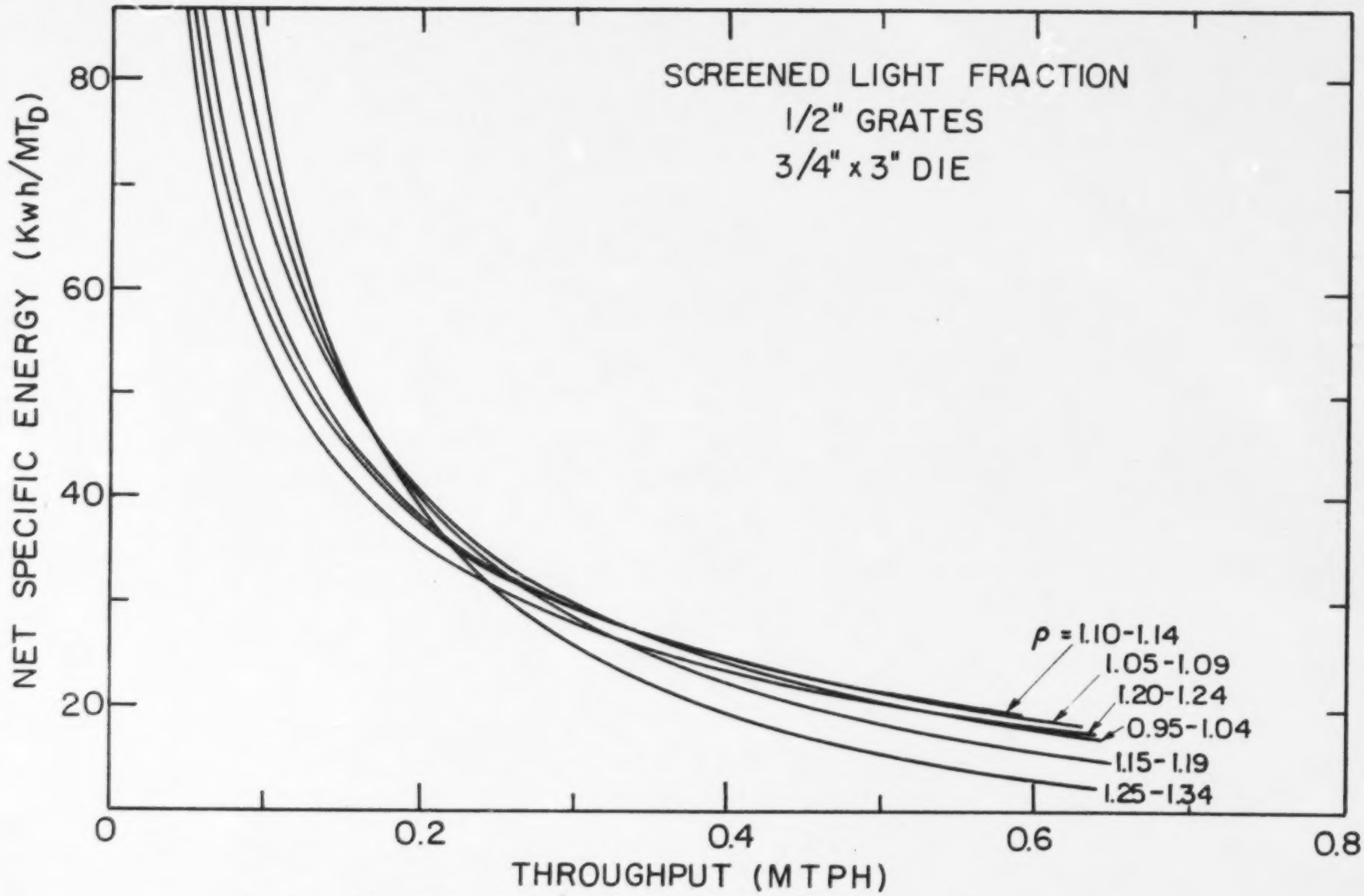


Figure 8 NET ENERGY VS. THROUGHPUT (dry basis)

provided the best analytical description. The coefficient, a, and exponent, b, vary with density. When the density range is between 1.15 and 1.19 g/cc, a = 10.477 and b = -0.834 ($r^2$ = 0.84). With the density range at 1.25 to 1.34 g/cc, a = 7.798 and b = -0.992 ($r^2$ = 0.93). When the data for the entire density range (0.95 to 1.34 g/cc) is considered, the constants in the equation are as follows: a = 10.698 and b = -0.823 ($r^2$ = 0.81). Results obtained with the use of a 1.0 in. by 5.0 in. die are plotted in Figure 9. An analytical correlation of the data yields the following coefficients: a = 19.6795 and b = -0.815 ($r^2$ = 0.96). In this particular case, the mill throughput was evaluated on a wet basis. The moisture content of the feed material was on the order of 15 percent.

The composition, size distribution, and characteristic particle size of feed material that has only undergone air classification differ from those of screened material. In some cases, the performance of the mill will reflect these differences. Such apparently was the case when unscreened lights were extruded through the 0.75 in. by 3.0 in. die. As shown in Figure 10, the slope of curves for specific energy as a function of throughput relation flatten at $\dot{M}_D$ values greater than 0.2 MTPH. In fact, the data tend to imply that within a small band of variation, the effect of throughput on specific energy cannot be discerned. However, this did not appear to be the case when the unscreened lights were forced through the 1.0 in. by 5 in. die. As indicated by the curve in Figure 11, the nature of the relationship between specific energy and throughput (dry basis) is comparable to the one described for screened lights. The relation continues to hold when the data are correlated with throughput on a wet basis, as is shown by the curve in Figure 12. The analytical representation yields the following coefficients: a = 18.38, b = 0.7485, ($r^2$ = 0.933).

In the part of the study that involved the densification of a coarse feed feed material, the screened lights were obtained from MSW that had been shredded with the grate spacing at 1.6 in. The screened lights were forced through a 0.5 x 4 in. die. The relation between specific energy and throughput as shown by the curves in Figure 13, indicates a discernible parametric feature with density and moisture content. The density of the pellet decreased with increase in moisture content, as is shown in Figure 13A. According to the curves in Figure 13B, the specific energy is generally enhanced on the order of a factor of two at a corresponding increase in moisture content in the throughput range of 0.2 to 0.4 TPH.

The effect of characteristic particle size on throughput is indicated by the curves in Figure 14A and 14B. The effect is plotted in terms of the characteristic particle size ($X_o$ at 63 percent passing) and of the nominal size (90 percent passing). It should be noted that because of the variations in feed rate of the MSW that normally occur in front-end processing, the characteristic particle size of the feed to the pellet mill can change, even though the configuration of the shredder and subsequent downstream unit operation do not change.

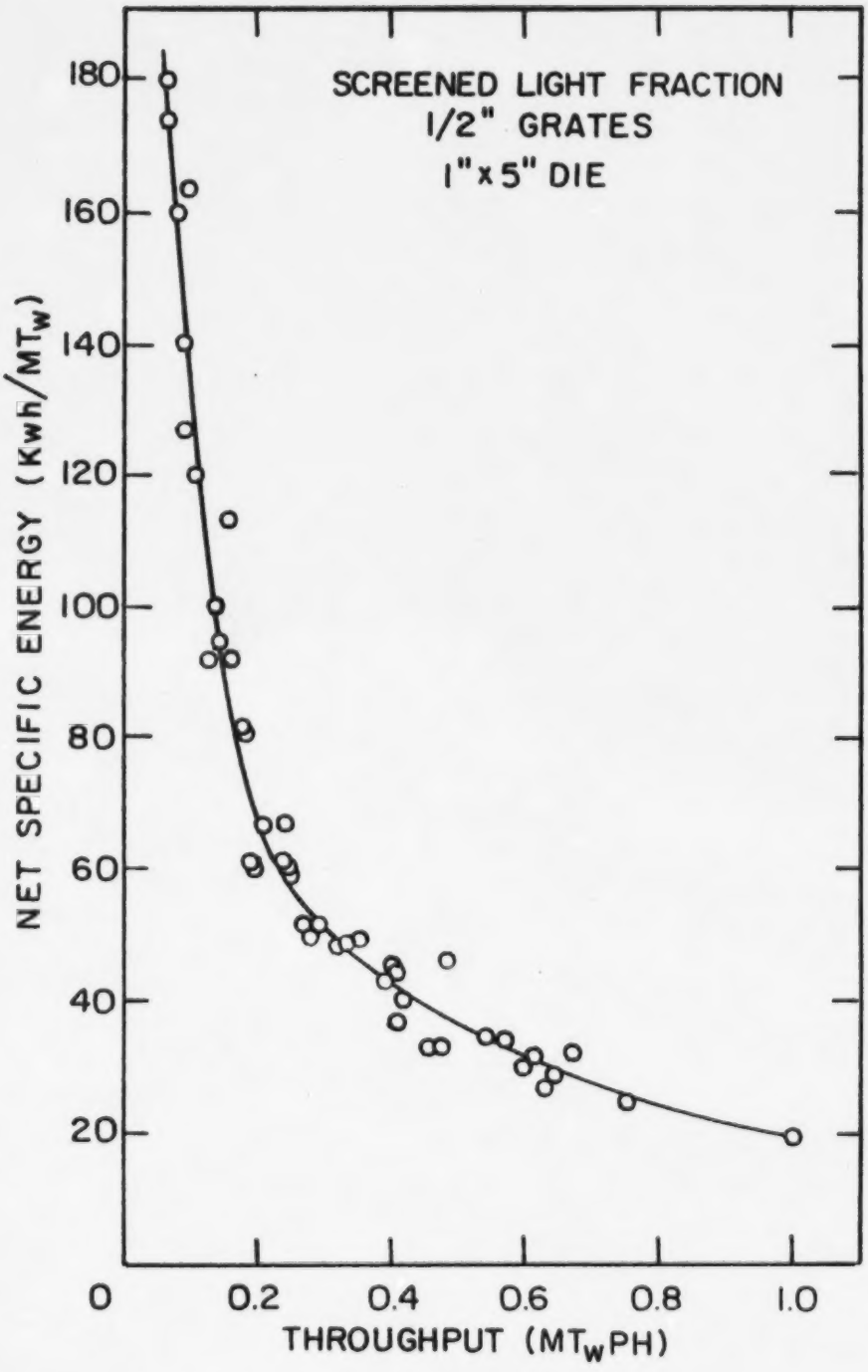


Figure 9 SPECIFIC ENERGY VS. THROUGHPUT
(wet basis)

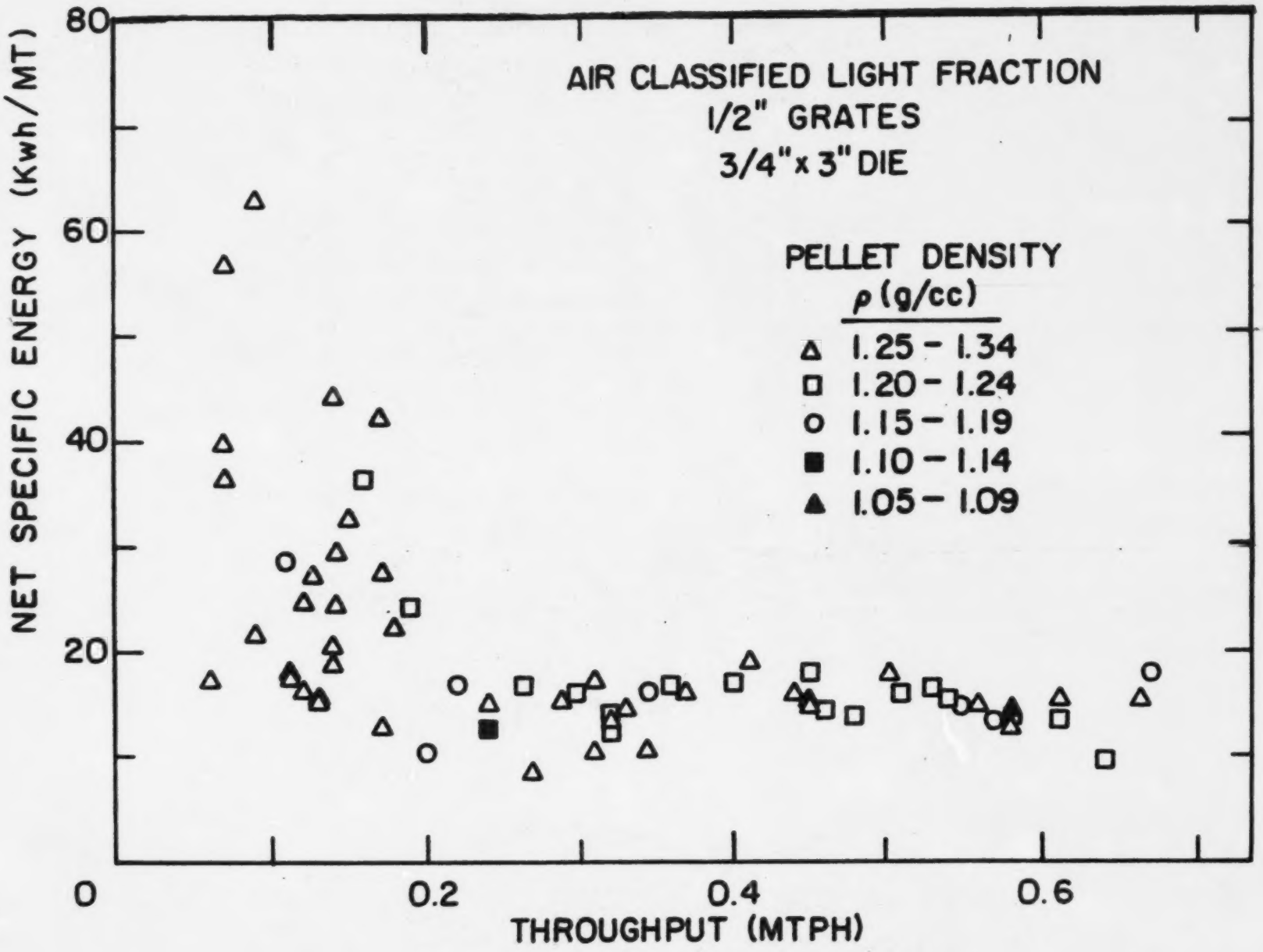


Figure 10 SPECIFIC ENERGY VS. THROUGHPUT (dry basis)

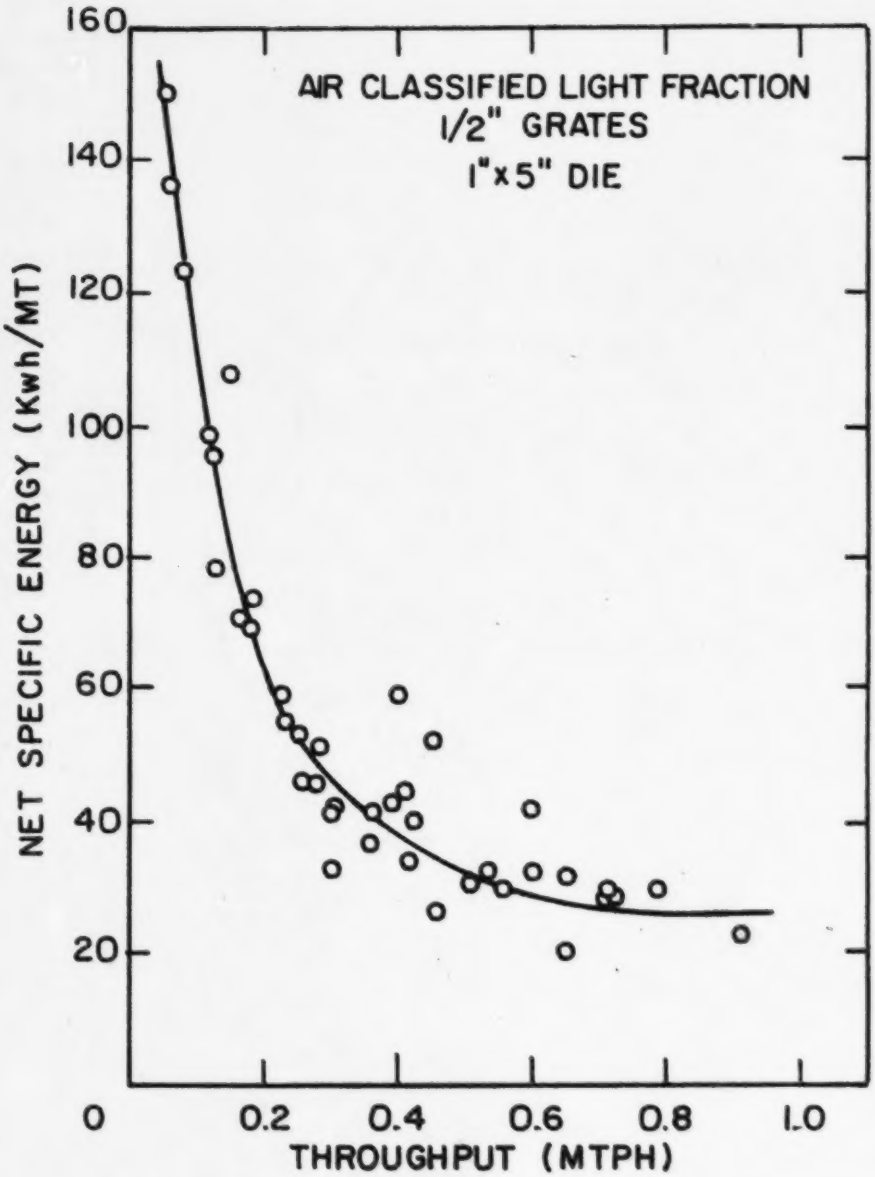


Figure II SPECIFIC ENERGY VS. THROUGHPUT
(dry basis)

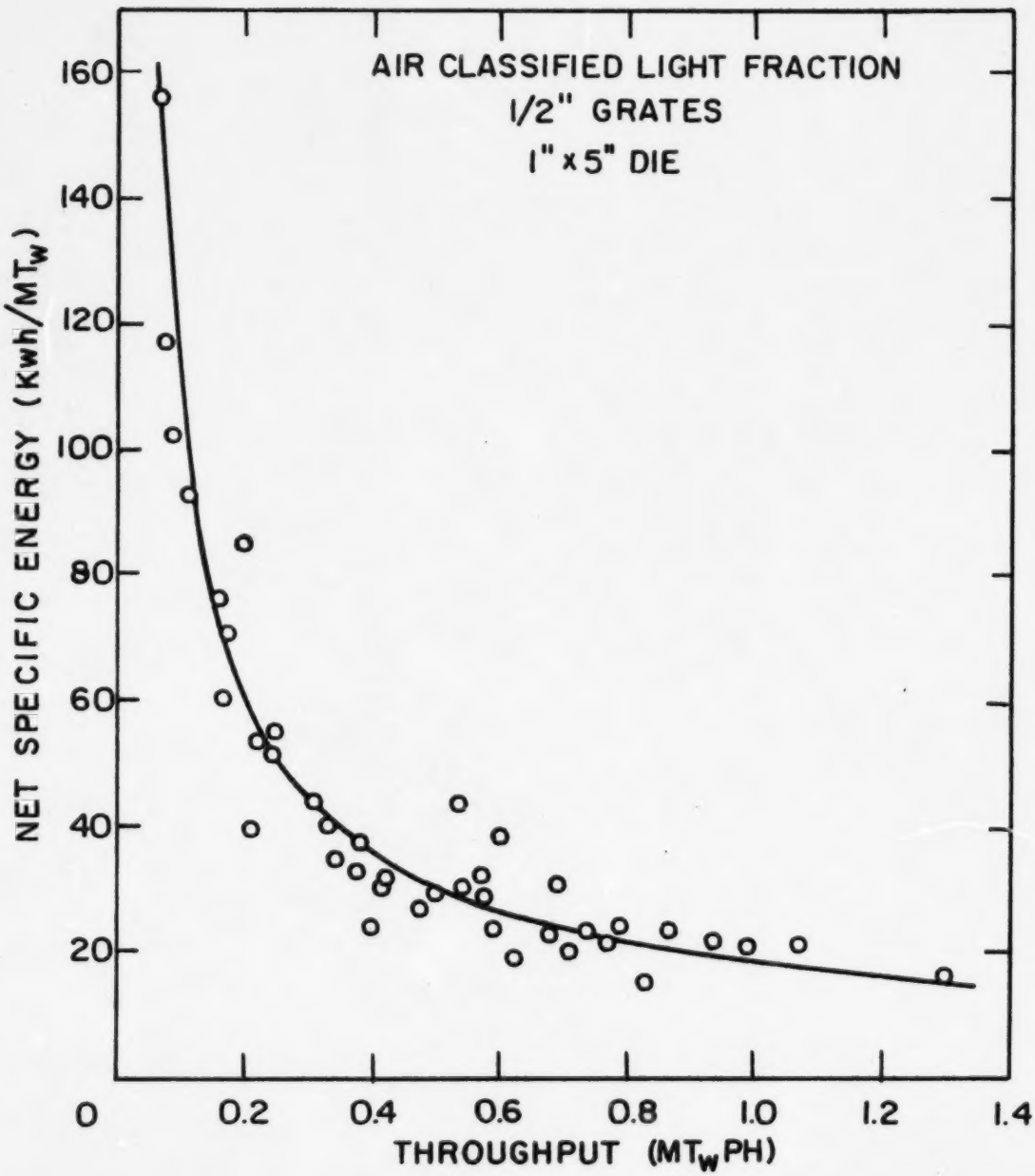


Figure 12 SPECIFIC ENERGY VS. THROUGHPUT (wet basis)

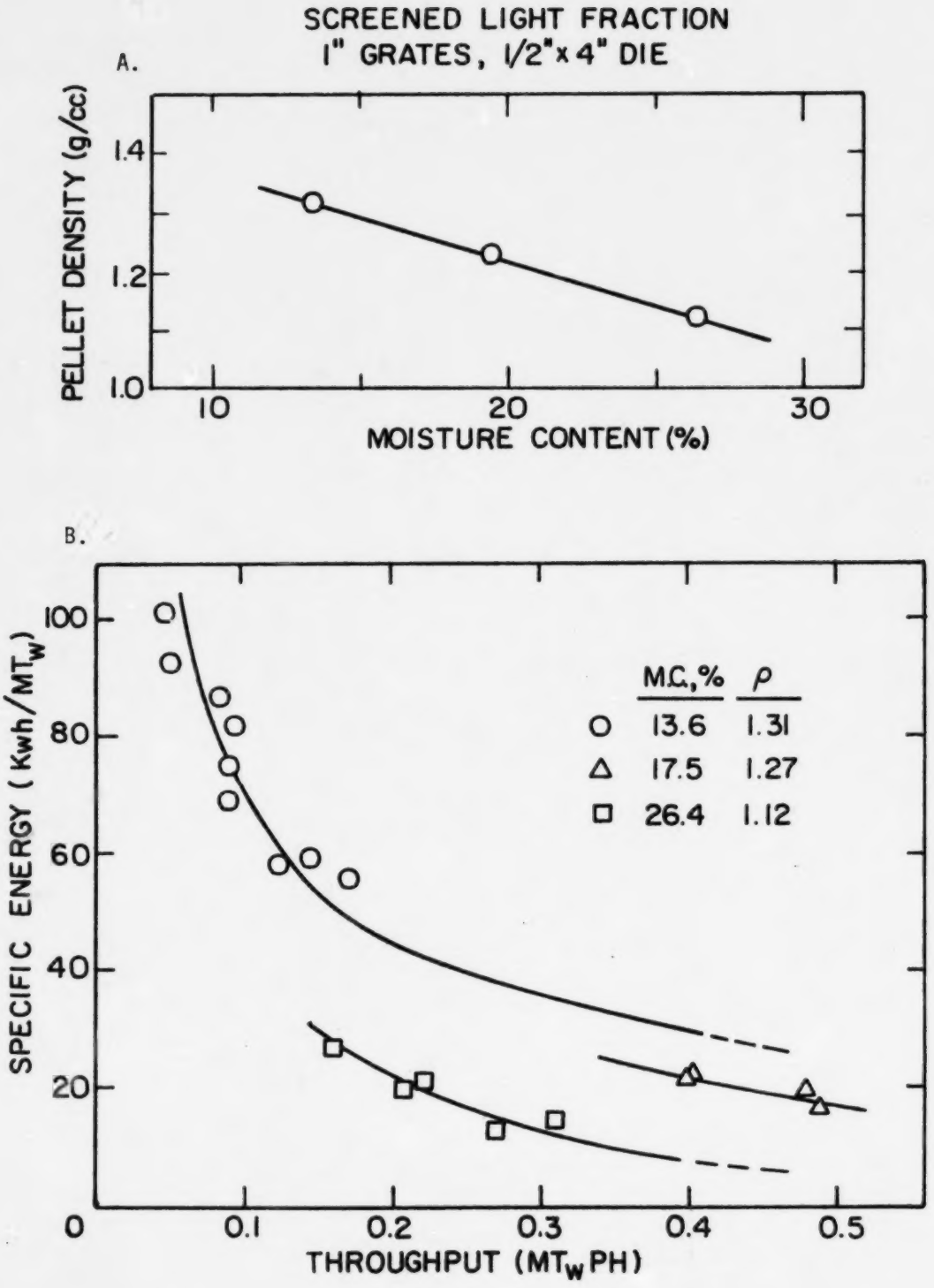


Figure 13 EFFECT OF MOISTURE CONTENT ON PELLET DENSITY AND SPECIFIC ENERGY

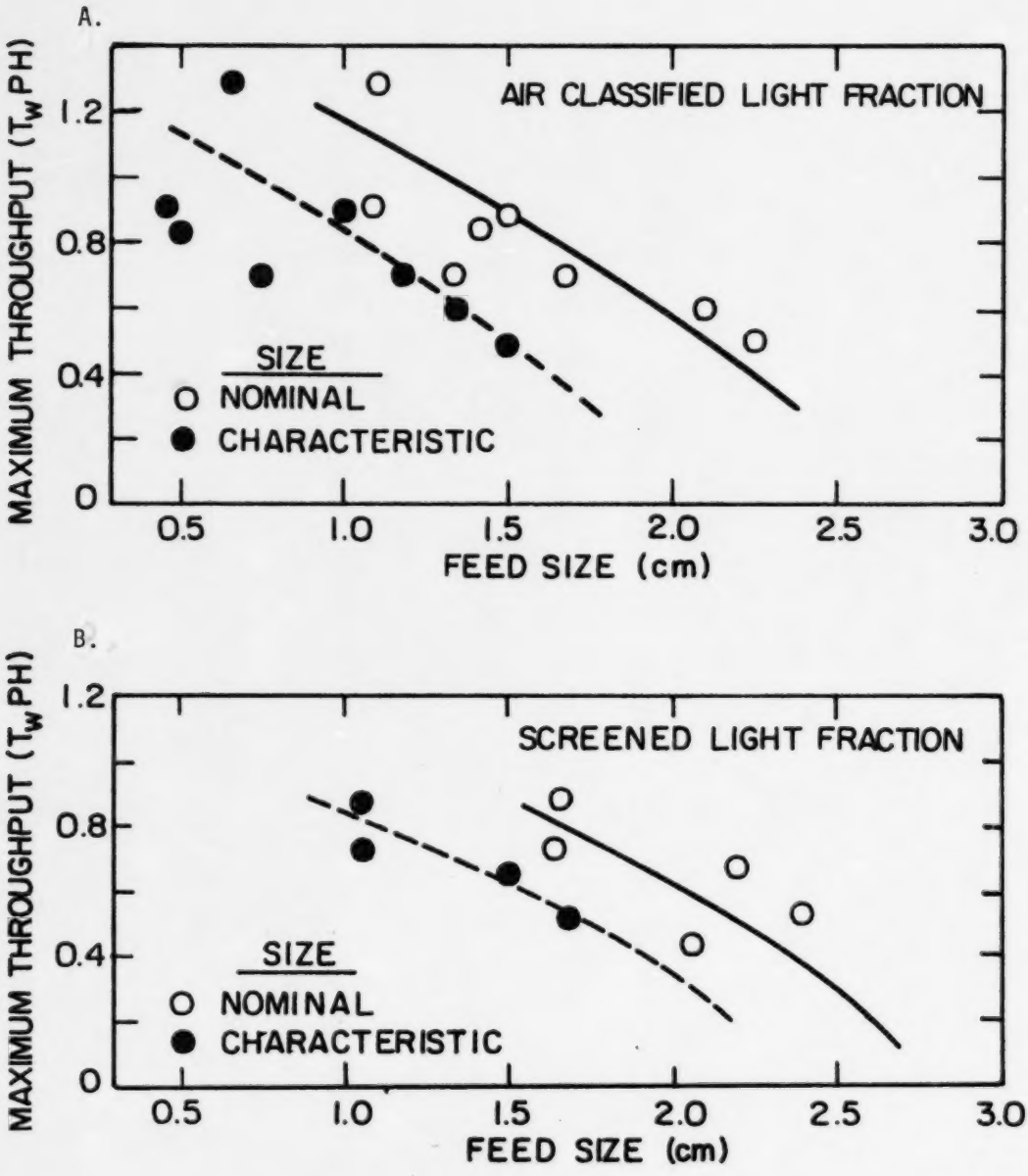


Figure 14 EFFECT OF FEED SIZE ON MAXIMUM VALUE OF THROUGHPUT

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# Section 4

# LABORATORY Ddensification STUDIES

## PURPOSE

As stated in the "INTRODUCTION", a series of single die experiments was undertaken in the hope of gaining a further insight into the physics involved in the densification of screened and unscreened light fractions of MSW -- or to express it more simply: to learn more about the fundamentals involved in the densification of RDF. The use of a single die is more suited to such a purpose, because a commercial machine cannot be manipulated to the degree and with the ease required to evaluate fundamental parameters. For example, it is difficult to evaluate the effects of die taper without incurring the expense of manufacturing custom dies. It also would be difficult to measure temperature in a rotating die.

An important purpose of the tests was to generate basic data that can be used by the industry either in retrofitting or in designing new densification equipment. Improved machines are needed to overcome the current problem of low throughput and extensive die wear.

## METHODS AND MATERIALS

A special die arrangement was constructed for the formation of pellets in a single die. The arrangement is shown in Figure 15. The basic assembly consisted of a rod, container, die, and support plate. The container is a 4 in. long cast-iron cylinder fitted with a removable cap to expedite cleaning. The dies were machined from high carbon steel, and had inside diameters of 1/2, 5/8, and 3/4 in. Each die was ground to have an outside diameter of one inch so as to provide a close sliding fit with the container. In addition to straight dies, taper angles of 2.4, 7.1 and 14 degrees on the radius were evaluated for the 3/4 in. die. Tapers of 0 (straight die) and 14 degrees were evaluated for the 1.2 and 5/8 in. diameter dies. The assembly was mounted in a standard laboratory Tinnius Olsen Universal Testing Machine. The latter machine is shown in Figure 16. The machine is a 160 mcap, 4-screw, electomatic style, and has a 160,000-lb capacity. The crosshead speed can be varied between 0.02 and 2 in./minute. Its motion, that is, the distance the die is pressed into the container, is measured with a deflectometer. A graph of force vs. deflection is generated on a high magnification recorder. The scales, 1600 lb for die friction test and 8000 lb for extrusion tests, had an accuracy of ≅ 0.2 percent during calibration.

Because of limitations imposed by the design of the test apparatus, two steps were required in the production of a pellet. In the first step, the

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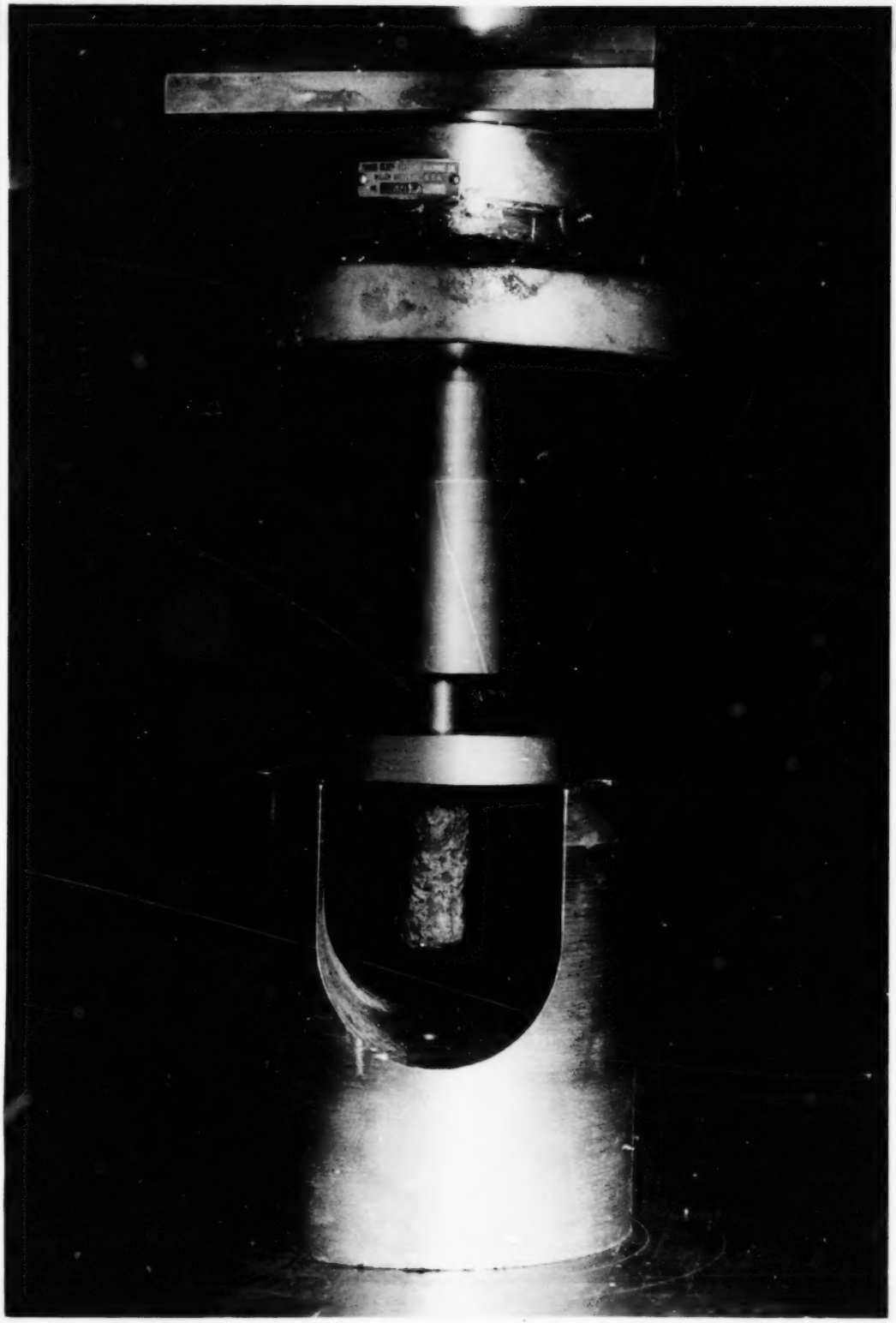


**FIGURE 15: APPARATUS FOR SINGLE DIE EXTRUSION TESTS**

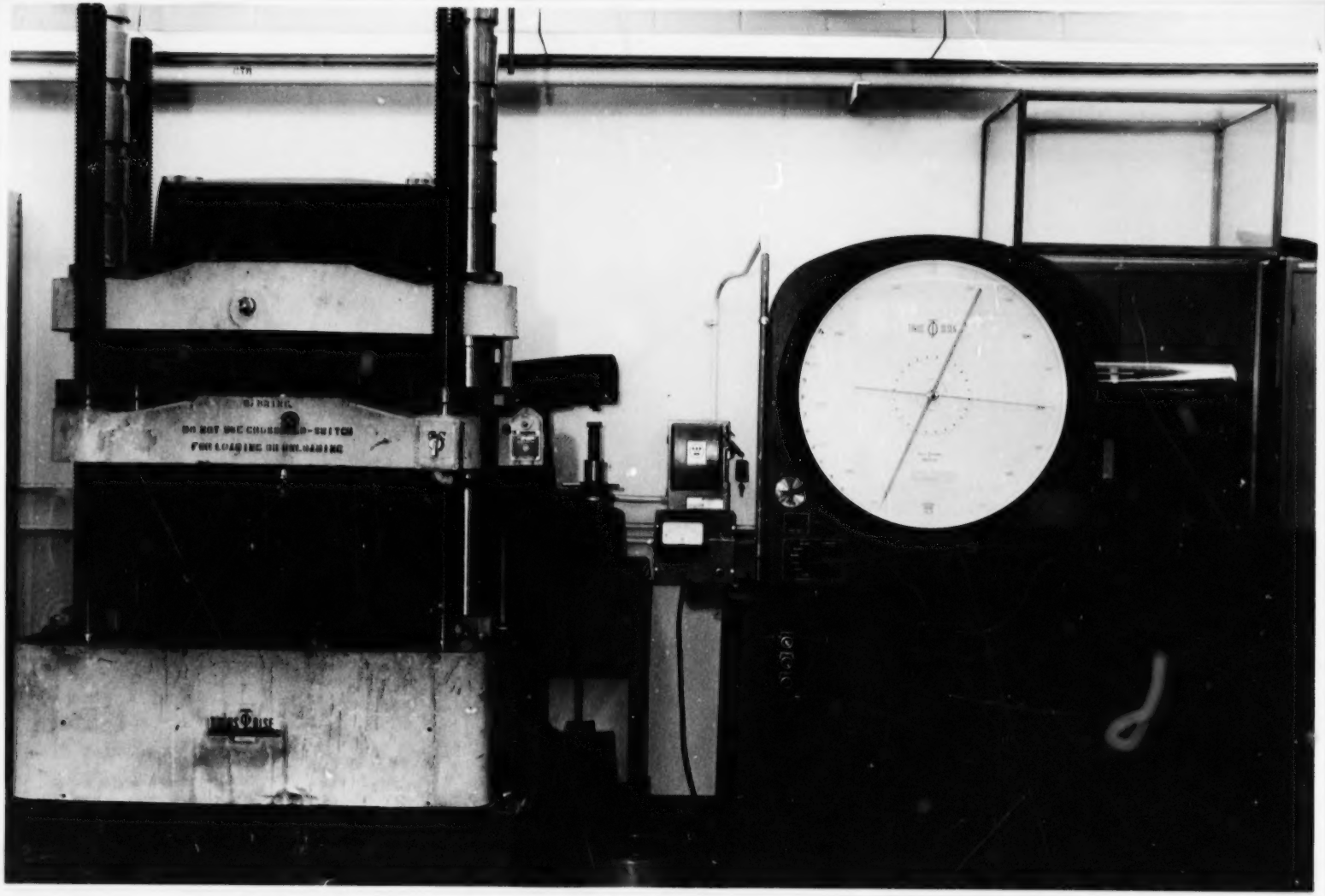


**FIGURE 16: COMPRESSION TESTER AND RECORDING EQUIPMENT USED IN SINGLE DIE STUDIES**

material to be pelletized was loaded into the container and the die and container assembly was positioned in the tester. Then upon actuation of the crosshead, the material was transformed from an uncompressed state in the container into a compressed state in the die. In the second step, a pellet is formed when the container is removed, reloaded, and the process is repeated. The sequence of pellet formation is illustrated in Figure 17. At the start of the sequence, two container reloadings are required to fill the die.

The feed material was prepared in the Solid Waste Processing Laboratory described in the section "PELLET MILL STUDIES." In this phase of the investigation, the screened light fraction of the MSW served as the feedstock in one set of experiments, and shredded newsprint in another. The final feed material for the first set was given a secondary size reduction by means of a WW fixed-hammer shredder. Grate openings of 1/2 in. were used with one part of the lights, and of 3/4 in. with the other part. All newsprint was shredded through the grates that had the 3/4-in. openings. The size distribution of the three feedstocks are indicated in Figure 18. Feestocks in certain of the tests were formed by adding newsprint equal to 25 and 50 percent of the lights.

In experiments concerned with the effects of temperature and moisture content on the densification process, the moisture content of the material was varied by adding a measured amount of water to air-dried material. In order to evaluate the effect of temperature, it was necessary to heat the material while it was in the die and container. Heating was accomplished by inserting the loaded die and container assembly into a laboratory oven and allowing them to remain there until the desired temperature was reached. Constraints imposed by the nature of the test apparatus required the use of such a method of heating. Obviously, the method of heating only approximates that which would be used in a commercial application. In the latter, the material most likely would be heated in a feeding chamber arrangement prior to being introduced into the die.

In the determination of die friction, a rod, slightly smaller in diameter than the internal diameter of the die, was used to push the material through the pre-loaded die. Essentially, the rod replaced the container in the test apparatus.

## ANALYTICAL MODEL

A simple first-order model was adopted to gain a further understanding of the physics of densification. The ability of the model to predict the energy needed to form a pellet is of particular interest. Power is a function of the flow rate of material through the die and the pressure required for extrusion. A schematic of the extrusion process and the resulting force balance on an elemental pellet volume are presented in Figure 19.

The total pressure is the sum of the pressure of deformation $P_D$ and the amount needed to overcome friction $P_F$. Following the approach used in metal extrusion, the pressure of deformation can be expressed in terms of the ratio of the initial material cross section, which in this case is the

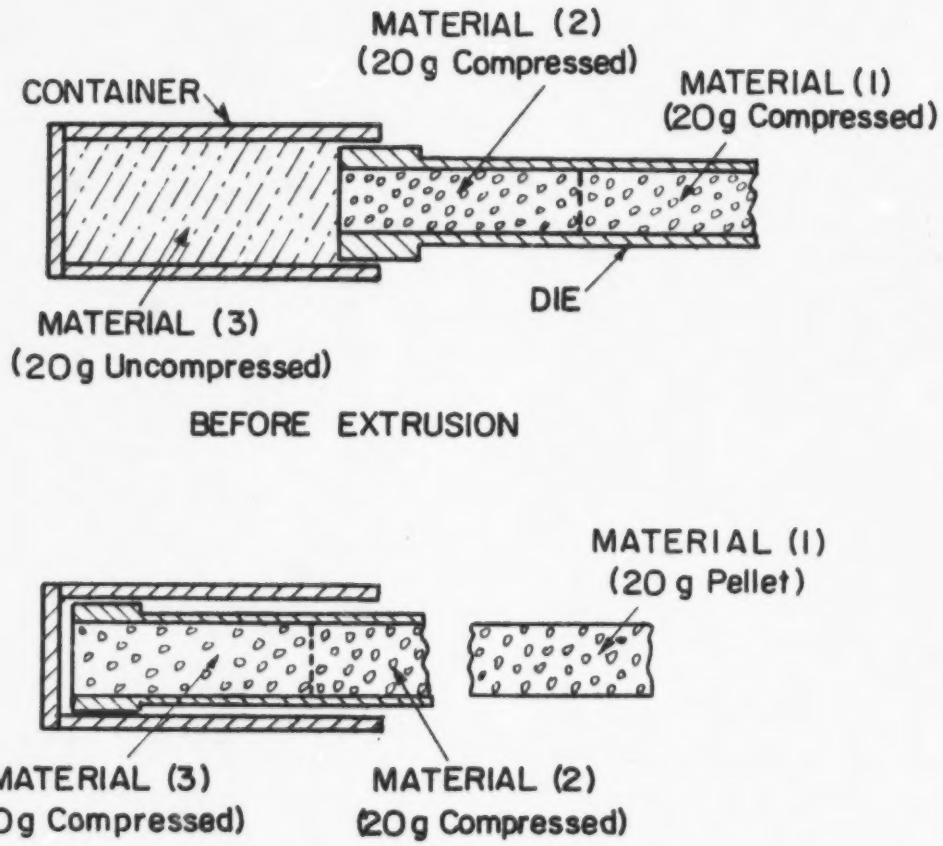



Figure 17 SEQUENCE OF PELLET EXTRUSION

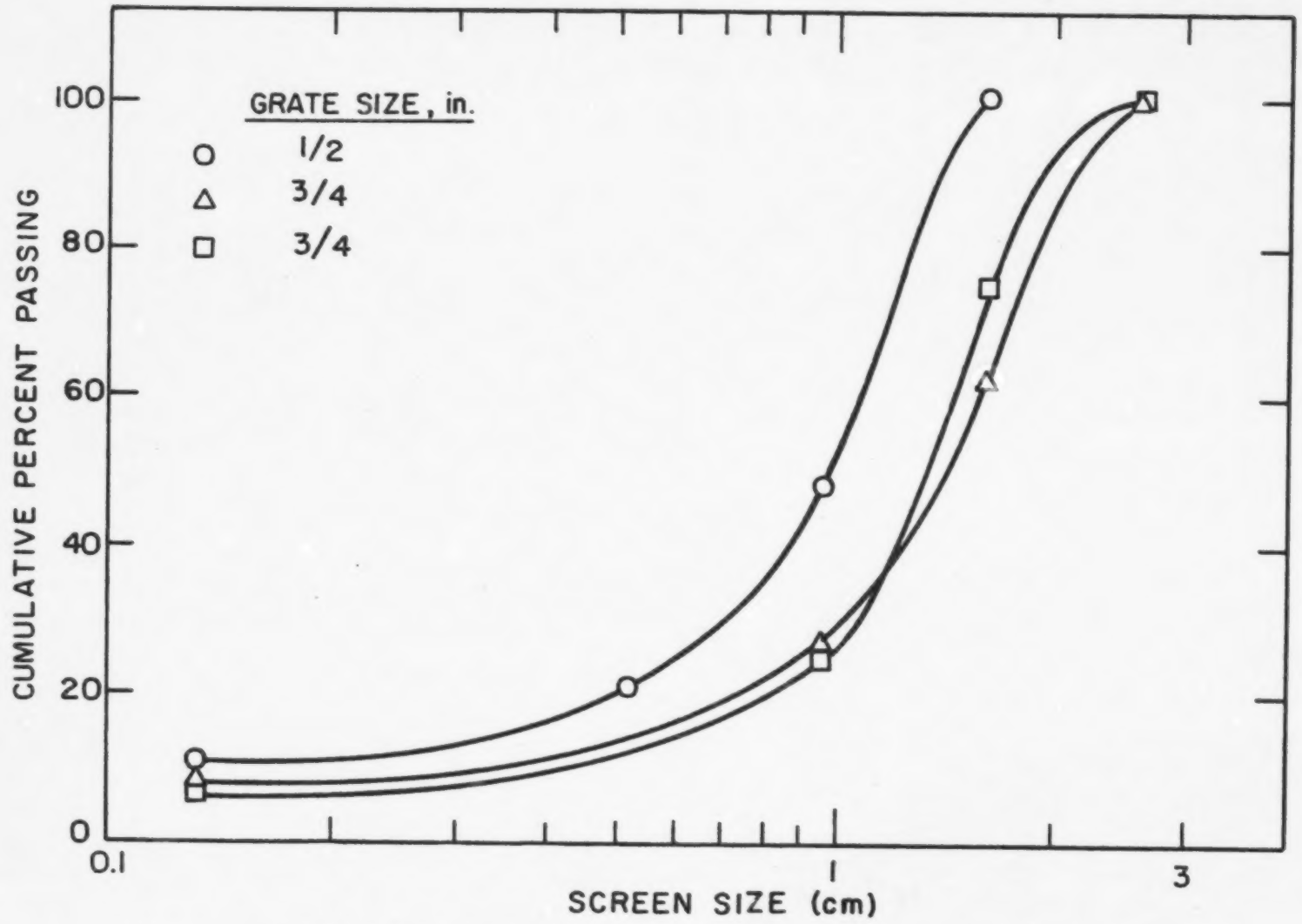
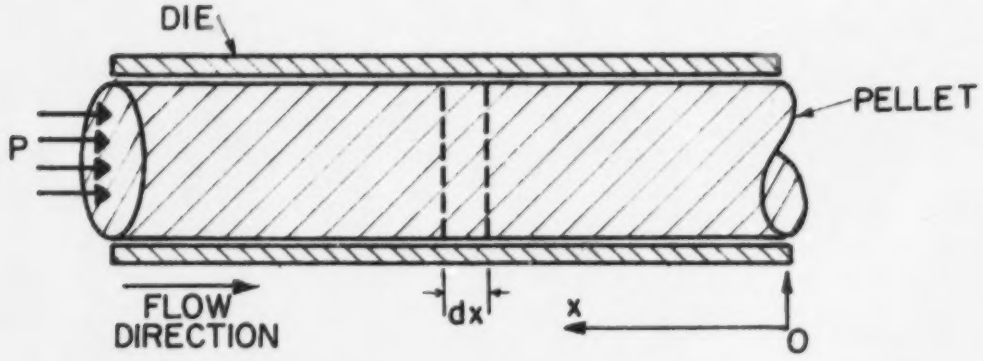
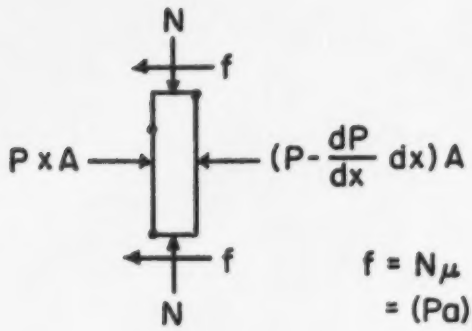



Figure 18 SIZE DISTRIBUTION OF SCREENED LIGHT FRACTION FEED USED IN SINGLE DIE EXPERIMENTS




$f = N\mu$
$= (Pa)\mu$
$= P\pi D\mu(dx)$

P = Pressure due to friction
$P_0$ = Pressure at x = 0
$\mu$ = Coefficient of friction
L = Die length
D = Die diameter

A = Die cross-sectional area
a = Die wall area
f = Frictional force
N = Normal force of wall on pellet

Force balance yields:

$$PxA = (P - \frac{dP}{dx}dx)A + P\pi D\mu(dx)$$

$$\frac{dP}{dx} = P\frac{\pi D\mu}{\pi D^2/4}$$

$$\frac{dP}{P} = \frac{4\mu}{D}dx$$

$$\ln P = \frac{4\mu x}{D}$$

$$\therefore P = P_0 \exp\frac{4\mu L}{D}$$

Figure 19 DERIVATION OF FRICTIONAL PRESSURE

cross sectional area of the container (A) and the cross sectional area of the pellet (a). Thus,

$$P_D = Y \ln A/a \quad (1)$$

where Y is the yield stress. The yield stress is a function of the orientation of the shear plane relative to the applied force and the conesiveness of the material being sheared. Since the shear plane influences the yield stress, in terms of the densification of MSW light fractions, Y should appropriately be referred to as "an apparent yield stress". Reasons for the qualification "apparent" are two in number: 1) The light fractions are non-homogeneous in content and each of their components has its particular yield stress. 2) Changes in die configuration, such as the inlet die taper, will change the plane at which shearing takes place.

An expression for the frictional contribution to the total pressure $P_F$ follows from a force balance on an elemental section. For the first order model, $P_F$ is given by

$$P_F = P_o \exp (4\mu L/D) \quad (2)$$

where $\mu$ is the coefficient of friction between the material (i.e. the pellet) and the die wall, and $P_o$ is an empirical constant. (The physical significance of $P_o$ is appropriately explained in a later section.)

Having determined $P_D$ and $P_F$, the energy required to form a pellet becomes

$$W = (P_D + P_F)(\text{Pellet Volume}) \quad (3)$$

The work required for densification is essentially the product of the pressure and the volume. In terms of the first order model, the work (W) given in terms of the above equations takes the form

$$W = W_D + W_F = V[Y \ln A/a + P_o \exp (4\mu L/d)] \quad (4)$$

However, as shown in Figure 20, in addition to the work of deformation and friction, there is an additional contribution to the total work due to the initial work required to compress the material. When the work is evaluated empirically by measuring the area under a local displacement curve, the work of compression is included. However, this contribution due to the initial exponential rise in load is not considered in equation 4.

The coefficient of die friction ($\mu$) can be determined by measuring the force required to push a formed pellet through the die. Since the force is the product of the pressure and the area, it follows from equation 2 that force and coefficient of friction are related by

$$F = F_o \exp [4\mu \ell/d] \quad (5)$$

where $F_o$ is an empirically determined constant and $\ell$ is the length of the pellet remaining in the die. In Figure 21 is shown a typical force vs. extrusion curve. It is based upon the die friction studies. A representative value for $F_o$ can be determined by the following:

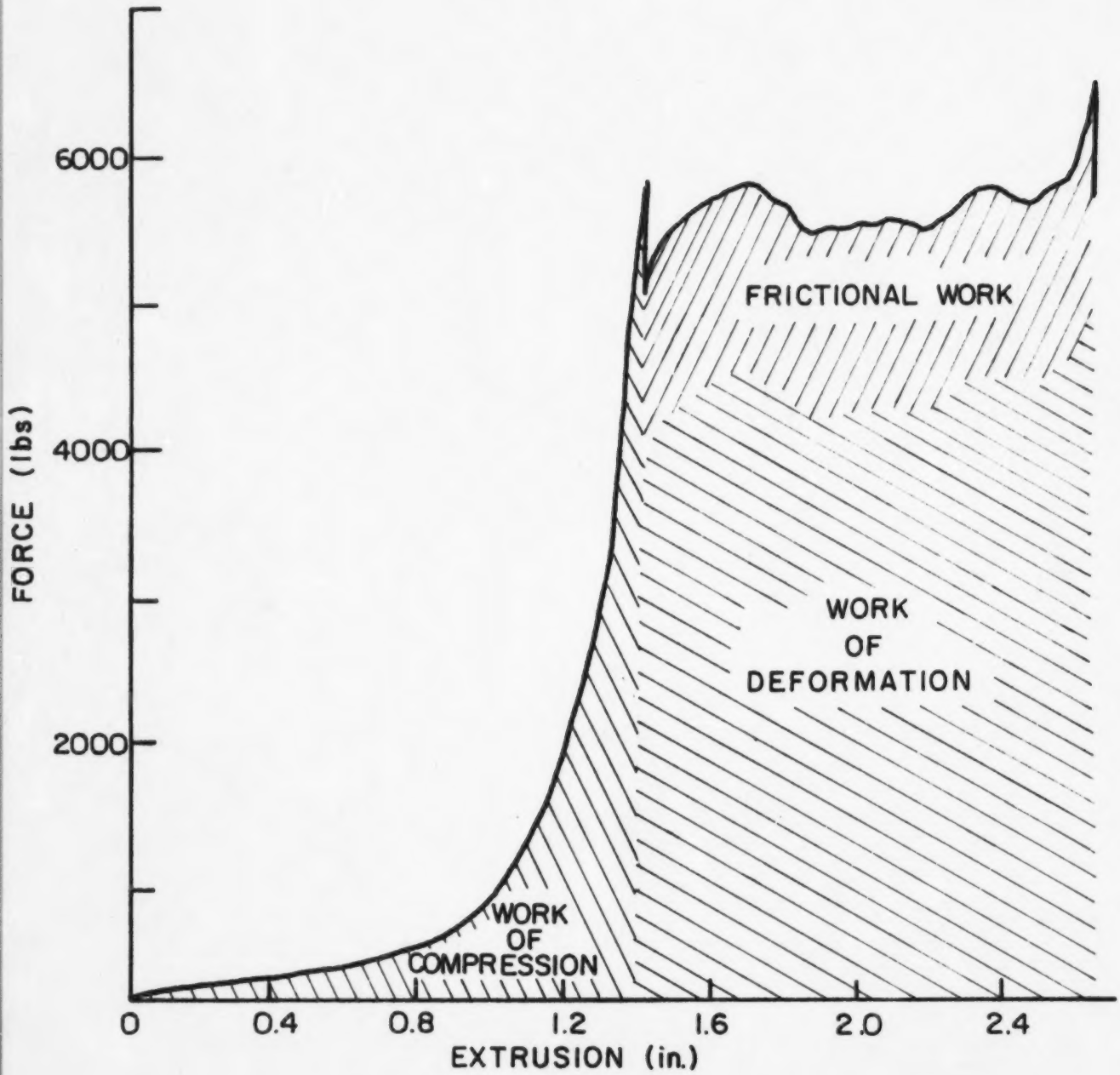



Figure 20 FORCE VS. EXTRUSION IN SINGLE DIE STUDIES

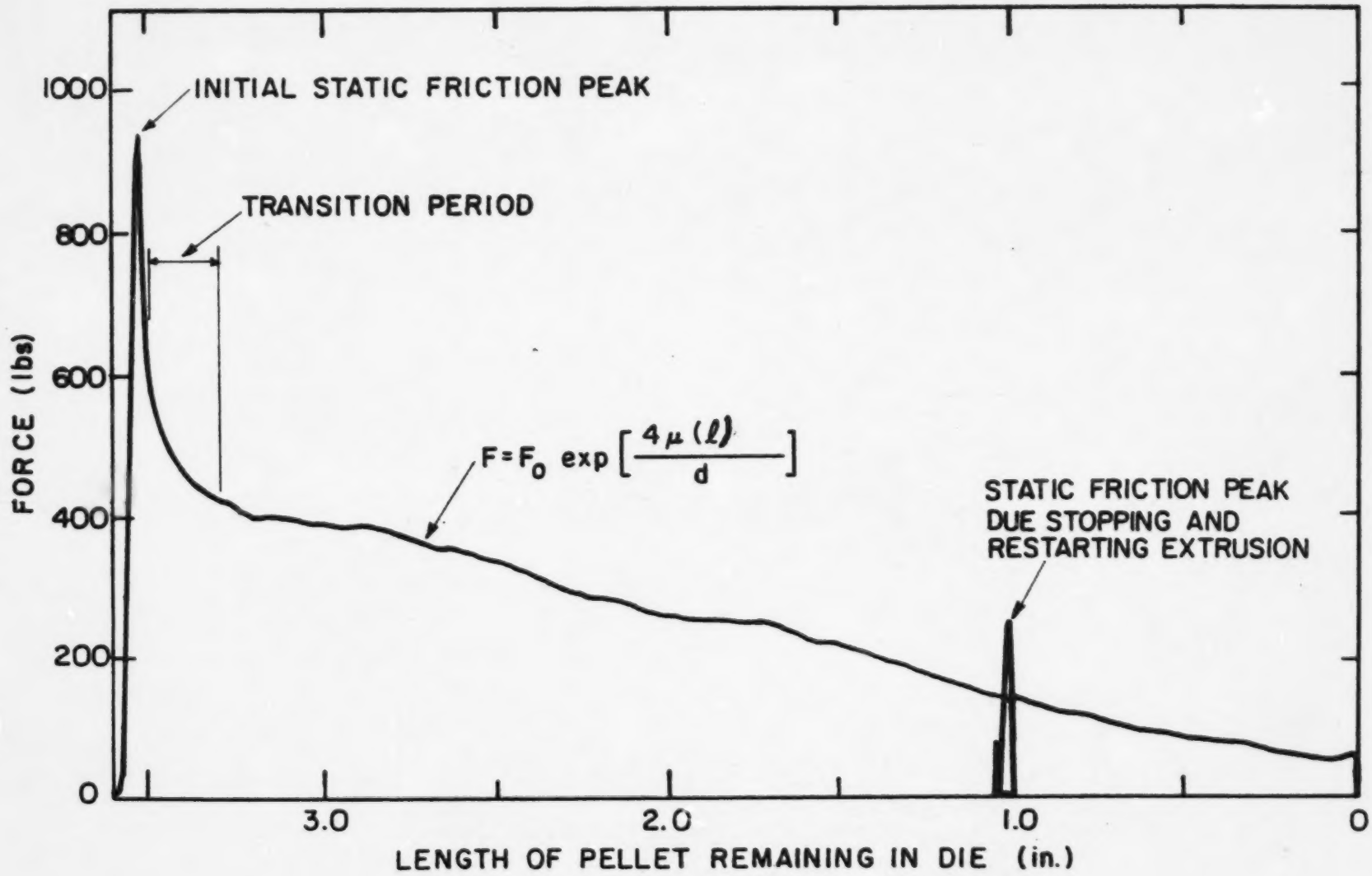



Figure 21 FORCE VS. PELLET EXTRUSION IN DIE FRICTION STUDIES

$$F_o = F_3 [4\mu \ell_3/d]^{-1} \quad (6)$$

where the subscript "3" refers to values at $\ell = 3$ in. The graph in Figure 21 may be used to determine the static coefficient of friction by considering the force required at $\ell = 1.0$ in. At this point, the flow was stopped and restarted to produce a static friction effect. The static friction can be calculated by

$$\mu st = (d/4\ell_{1.0}) \ln (F_{1.0}/F_o) \quad (7)$$

## DISCUSSION OF RESULTS

In this section is considered the manner in which the major parameters of die friction, flow rate, moisture content, temperature, and material composition affect the densification process.

### The Die Friction Curve

A typical load curve is shown in Figure 21. The excessively high initial static friction peak in the curve is due to start-up artifacts. It is followed by a short transition region. The portion of the curve between 3.0 to 3.0 (Figure 21) is indicative of the dynamic friction of the pellet sliding through the die, and it can be represented by equation 5. The peak at x = 1.0 is due to the static friction of stopping and then re-starting the pellet movement through the die. The value of dynamic friction over a range of motion ($\mu_{ave}$) can be obtained by applying equation 5 at various points. For example, over the range of $1.5 \leq \ell \leq 3.0$, $\mu_{ave}$ is given by

$$\mu_{ave} = \frac{d}{4(\ell_{3.0} - \ell_{1.5})} \ln (F_{3.0}/F_{1.5}) \quad (8)$$

### Force vs. Compression Curves

The force-compression curve shown in Figure 22 is an example of the actual plots made by a recorder controlled by the Tinius-Olsen compression tester and deflectometer. The four curves in the figure represent results obtained with four pellets; therefore, one curve for each pellet. Essentially, each curve is a plot of the compressive force (in pounds) versus the distance to which the die is pressed into the container (for 4 pellets) is shown. Each division on the horizontal axis corresponds to 0.4 in. of compression (or crosshead motion).

The curves bring to the fore, four distinct regions of interest:

1) In region 1, the loose material is compressed to form a compact cylinder in the container. The force in this region rises exponentially as the material is compressed.

2) In region 2, the material begins to move through the die. The onset of motion results in a precipitous drop in force, corresponding to the transition from static to kinetic friction.

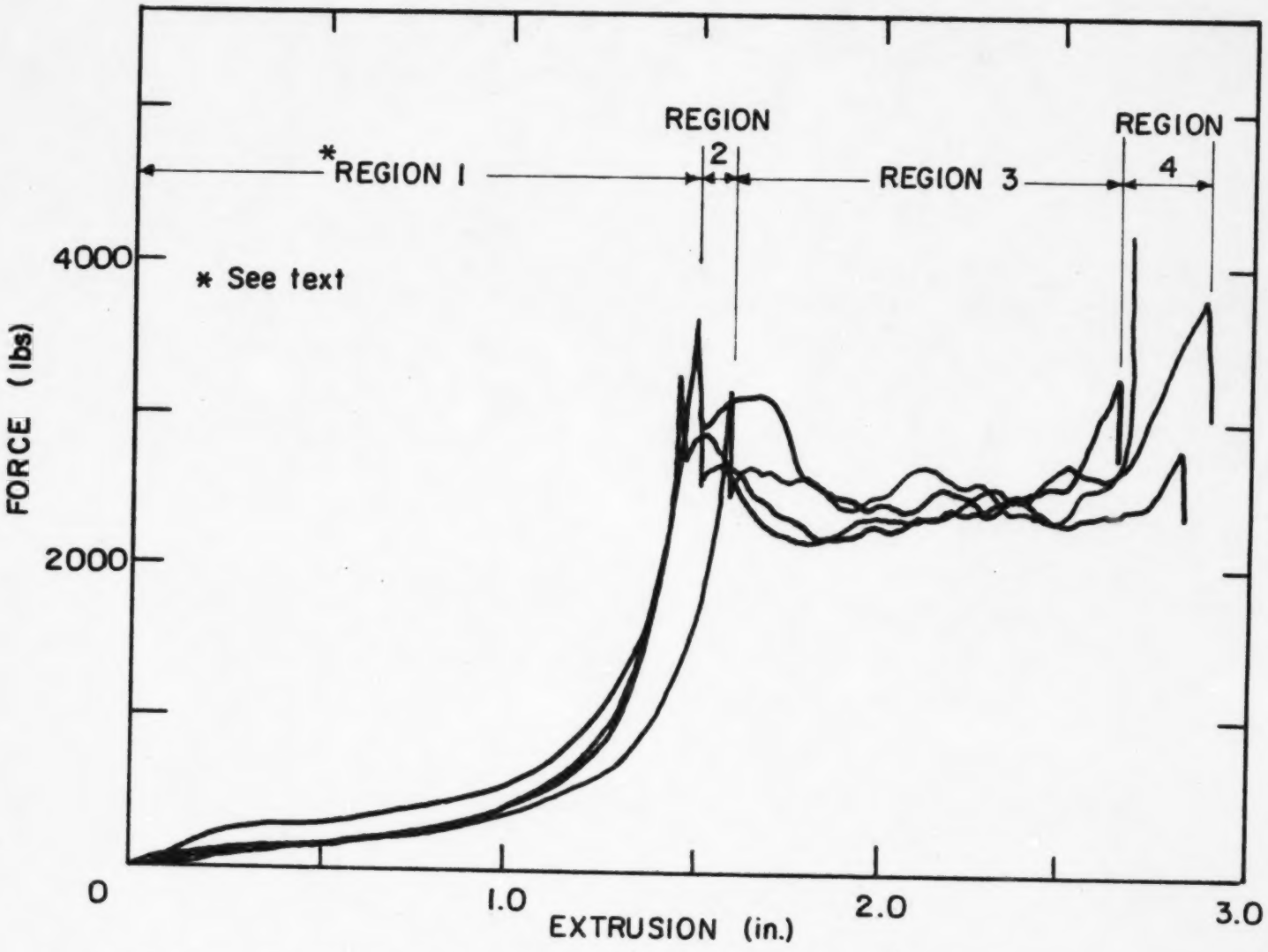



Figure 22 TYPICAL FORCE VS. EXTRUSION CURVES FOR SINGLE DIE STUDIES

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3) In region 3, the pellet is extruded from the die. The force fluctuations are attributable to non-homogeneity of the material. The magnitude of the fluctuations is typically from 5 to 15 percent of the extrusion force.

4) In region 4, the force surges rapidly as the amount of material remaining in the container approaches zero. The surge occurred consistently whenever the length of the material remaining in the container was less than about 1/4 in., i.e., when the die had less than 1/4 in. of potential travel remaining before contacting the end of the container. This phenomenon is also observed in metal extrusion. It is explained by the change in direction of flow lines. When the length of material in the container exceeds the diameter of the die, the flow lines tend to be almost parallel to the axis of the container. At the die inlet, they curve gently, radially inward. When the length of material in the container becomes less than the die diameter, the flow lines become oriented in a more radial direction. This radial flow of material requires a greater deformation force than does a longitudinal flow. While the flow lines of solid waste were not observed in these experiments, it is reasonable to assume the occurrence of a phenomenon similar to that in metal extrusion.

The pressure rise in region 4 has some very significant potential applications in the large scale densification of RDF. Since the pressure rise corresponds to an increase in energy consumption, specific energy consumption can be reduced in two ways:

1) Maintain a suitable clearance (1/4 in. or more) between the die inlet and the object used to force material into the die. In commercial pellet mills, the object is a roller. Experience indicates that a 1/4 in. clearance between roller and die will not yield forces great enough to bring about a flow of material.

2) Increase the amount of material extruded per pellet. Since the pressure rise occurs once for each pellet, specific energy can be minimized by extruding a maximum amount of material per pellet. Experimental data obtained from a commercial pellet mill clearly confirm this trend.

   Elsewhere in this report it is indicated that increasing the pellet flow rate by a factor of four results in no change in the pressure required for extrusion. There is no theory to predict that merely changing the pellet velocity would change the specific energy consumption. This phenomenon, illustrated in region 4, shows that increasing the flow rate in a commercial pellet mill can reasonably be expected to result in a drop in specific energy consumption, even though the velocity in itself has no effect on energy consumption.

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The rapid rise in pressure caused by a change from longitudinal flow to radial flow may also account for the die wear that occurs in commercial pellet mills. The wear is of two types: 1) Erosion at the die inlets, and 2) spalling on the cylinderical face of the die. Erosion is aggravated by increased pressure. Spalling (pitting) occurs on the cylindrical face of the die, i.e. the area of contact between the rollers and the die. Spalling is caused by a combination of compressive and shear stresses upon the face of the material being worn. As explained above, the rapid rise in compressive forces is accompanied by a transition in the direction of flow from nearly perpendicular to parallel to the face of the die. Parallel flow results in shear stresses upon the die face, and when these shear stresses are coupled with increased compression stresses, conditions for spalling are optimized.

Effect of Parameters on Friction

The manner in which the major parameters affect the die friction is summarized in Table 2. The pellet expansion, given by the ratio of the pellet diameter to the die diameter, is due to the fact that a pellet expands slightly (rebound) after it leaves the die. In order to establish a basis of comparison, an extrusion rate of 1 in./min was selected as the standard rate. In general, for the series of die friction experiments, the static friction typically is on the order of 50 to 100 percent greater than the dynamic friction.

The effect of moisture was determined by forming pellets with material, the moisture content of which was varied between seven and twenty-one percent. Pellets formed at 21 percent moisture content had the lowest density and greatest degree of expansion, and were characterized by the highest values of $\mu_{ave}$ and $\mu_{st}$. These trends may be due to the compressibility or "sponginess" that is characteristic of very moist pellets.

In general, friction coefficients decrease with increase in moisture content. However, pellets formed of material having a low moisture content are characterized by excessive flakiness and by high deformation forces. It is interesting to note that according to Table 2, increasing moisture content results in an initial increase and subsequent decrease in $F_O$. Basically, $F_O$ is a direct function of $\mu$, radial expansion of the pellet, and pellet density or hardness. Expandibility and density determine the amount of radial force that must be exerted by the die wall in order to contain the pellet. The product of this radial force and $\mu_{ave}$ yields the frictional force. At a moisture content of 20 percent, expandibility is high (1.08) but density is low (0.8). Therefore, the resultant value of $F_O$ is low, and the pellet is soft and spongy. As the moisture content is decreased, the density increases, and the result is a subsequent increase in $F_O$. However, if the moisture content is further decreased, both expandibility and $\mu$ will decrease, and the effect of increased density will thereby be counteracted. The result is a decline in the value of $F_O$.

As stated earlier, the nature of the single die experiments was such that the thermal effect could be considered only by heating the material after it had been loaded into the container, prior to extrusion through the die. Consequently, the results obtained by using this experimental

procedure may not be completely indicative of what can be expected in the densification of pre-heated (i.e. "externally" heated) material. For example, in the series of experiments, it was observed that temperature did not affect the overall force of extrusion, and moreover, most of the effect apparently due to temperature could be attributed to experimental procedure. Nevertheless, it is of interest that the length of time the material remained in the container and die assembly increased considerably with increase in temperature. Apparently, because of the thermal compaction of the 200°F material contained in the die during the stay in the oven, the pellets did not expand after they were formed. Furthermore, the subsequent values of $P_o$ and $F_o$ were significantly lower than those measured when the material was held at 150°F. The pellet formed from material heated to 200°F had a smooth glazed like surface and a tightly formed internal structure.

TABLE 2. DIE FRICTION

| Condition of Feed | $\mu_{ave}$ | $P_o$ (Psi) | $\mu_{st}$ | Pellet Dia. / Die Dia. |
|---|---|---|---|---|
| Velocity | | | | |
| 1/2"/min | 0.10 | 174 | 0.16 | 1.08 |
| 1"/min (standard) | 0.09 | 199 | 0.14 | 1.06 |
| 2"/min | 0.08 | 197 | 0.13 | 1.08 |
| Moisture Content | | | | |
| 21 percent | 0.10 | 115 | 0.16 | 1.08 |
| 16 percent (standard) | 0.10 | 147 | 0.16 | 1.08 |
| 14 percent | 0.09 | 177 | 0.12 | 1.06 |
| 10 percent | 0.07 | 199 | 0.13 | 1.06 |
| 7 percent | 0.06 | 158 | 0.12 | 1.04 |
| Temperature* | | | | |
| 70 (standard) | 0.10 | 147 | 0.16 | 1.08 |
| 150/170 | 0.07 | 244 | 0.11 | 1.06 |
| 200/330 | 0.08 | 131 | 0.11 | 1.00 |
| 200/600 | 0.10 | 131 | 0.15 | 1.00 |
| Newsprint Added | | | | |
| 0 percent (standard) | 0.10 | 147 | 0.16 | 1.08 |
| 25 percent | 0.09 | 258 | 0.13 | 1.04 |
| 50 percent | 0.09 | 471 | 0.09 | 1.04 |

Standard Conditions: Material - SLF (3/4" grates), die diameter = 3/4"
Velocity = 1"/min, Temperature = 70°F

* Temperature is given as material temperature/oven temperature (°F)

When the pellets were formed from feedstock consisting of light fraction feed materials to which 25 percent and 50 percent newsprint had been

added, the force that had to be applied became greater in proportion to the extent that the composition of the feedstock was oriented toward being of a single species. As is indicated by the data in Table 2, the increase is reflected in the substantial increase in pressure $P_0$ as compared with the corresponding values obtained with screened lights alone ("standard" pellets). Observations showed that the pellets formed with high concentration of newsprint were essentially harder than the "standard" pellets. Of the two types, the pellets that contained newsprint had a higher density and were more difficult to break. The value obtained for $\mu_{ave}$ is similar to that obtained for a "standard" pellet; whereas $\mu_{st}$ is lower, particularly when the newsprint fraction is 50 percent. At that point, the value of $\mu_{st}$ (0.09) is nearly a factor of two less than that for the "standard" pellet (0.16), and is of the same order as $\mu_{ave}$.

Effect of Moisture Content and Die Taper on Deformation Pressure

The deformation pressure, $P_D$, is obtained from the standard force compression curve essentially by converting the force to pressure and subtracting the effect of friction ($P_F$). A computation of the data plotted in Figure 23 illustrates the dependence of deformation pressure upon moisture content. Within the scope of the series of single die experiments reported herein, the results were parametric with die taper. Within the range of conditions prevailing or applied in the experiments, flow rate and temperature did not significantly influence the deformation pressure. The influence of moisture content is somewhat analogous to that observed in soil mechanics. Essentially, as the moisture content increases, the material becomes less viscous. As a result it becomes easier to deform and in effect, easier to push through the die. However, consistent with the preceding discussion, the addition of moisture does not serve to lubricate the die walls.

The fact that the values obtained with the straight die (0° taper) lie between those for the 7° and 14° tapers can be explained to some extent by the physical characteristics of the pellets. No difference could be discerned between the strength of pellets formed in the 0° and those formed in 7° taper dies. On the other hand, pellets formed with the 14° die were consistently better in quality, than were those formed with the 0° and the 7° dies. Even though the pellets produced with the 14° die had a lower density, they were in effect better formed because the material was interwoven such that the pellets could not easily be broken.

At the lower moisture contents the outside surface of the pellet tended to be flaky. Increasing the moisture content brought about the formation of a smoother surface. This smoothening effect continued until a moisture content of 20 percent was reached. As the moisture content began to exceed 20 percent, the surface again tended to flake, and the pellet became weak and spongy. The relation between density and moisture content for this series of experiments is indicated by the curve in Figure 24.

Effect of Die Diameter on Deformation Pressure

In Table 3 are listed data on the pressure of deformation ($P_D$) of pellets formed of material shredded with the shredder grate openings at

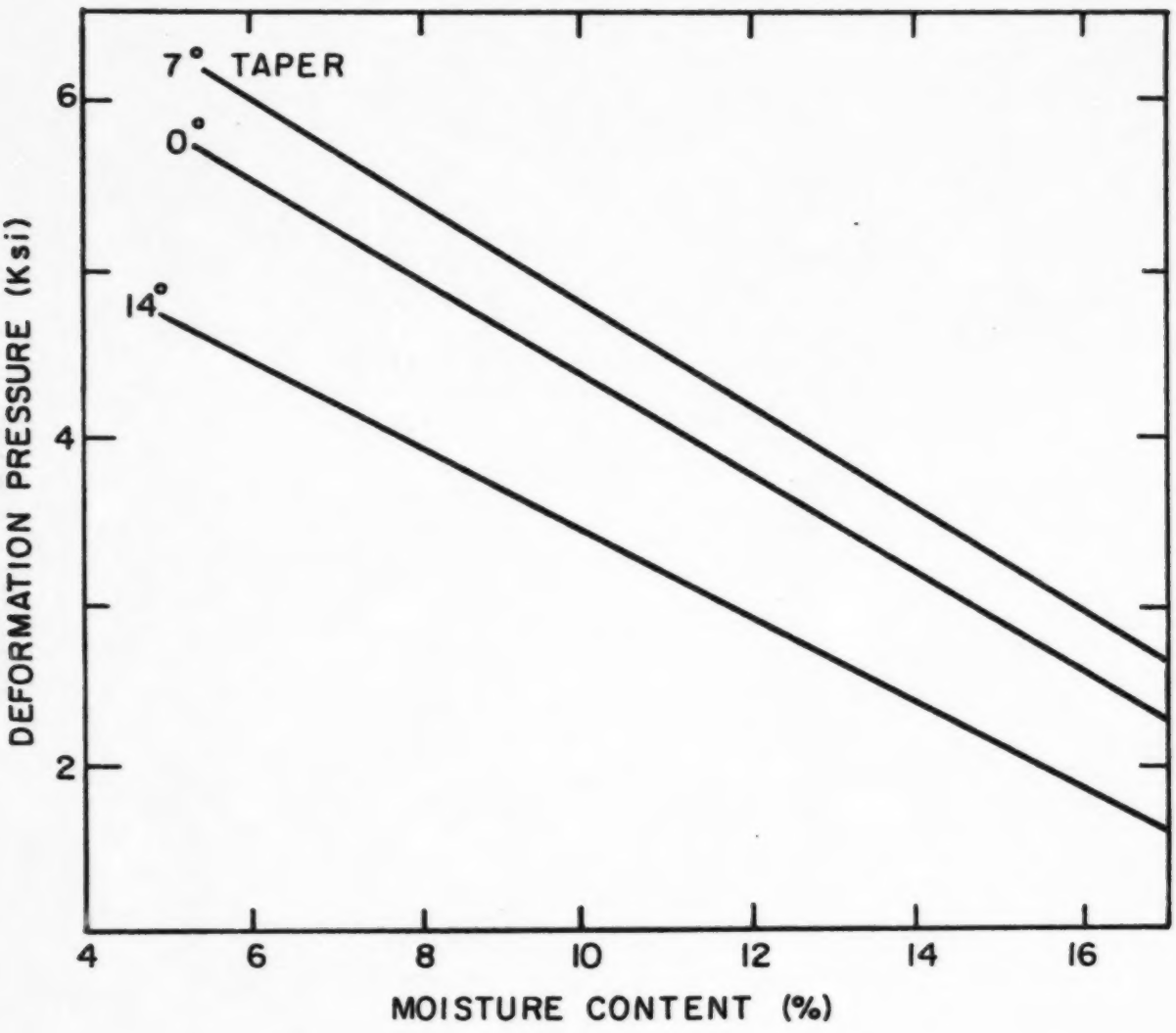


Figure 23 DEFORMATION PRESSURE VS. MOISTURE CONTENT

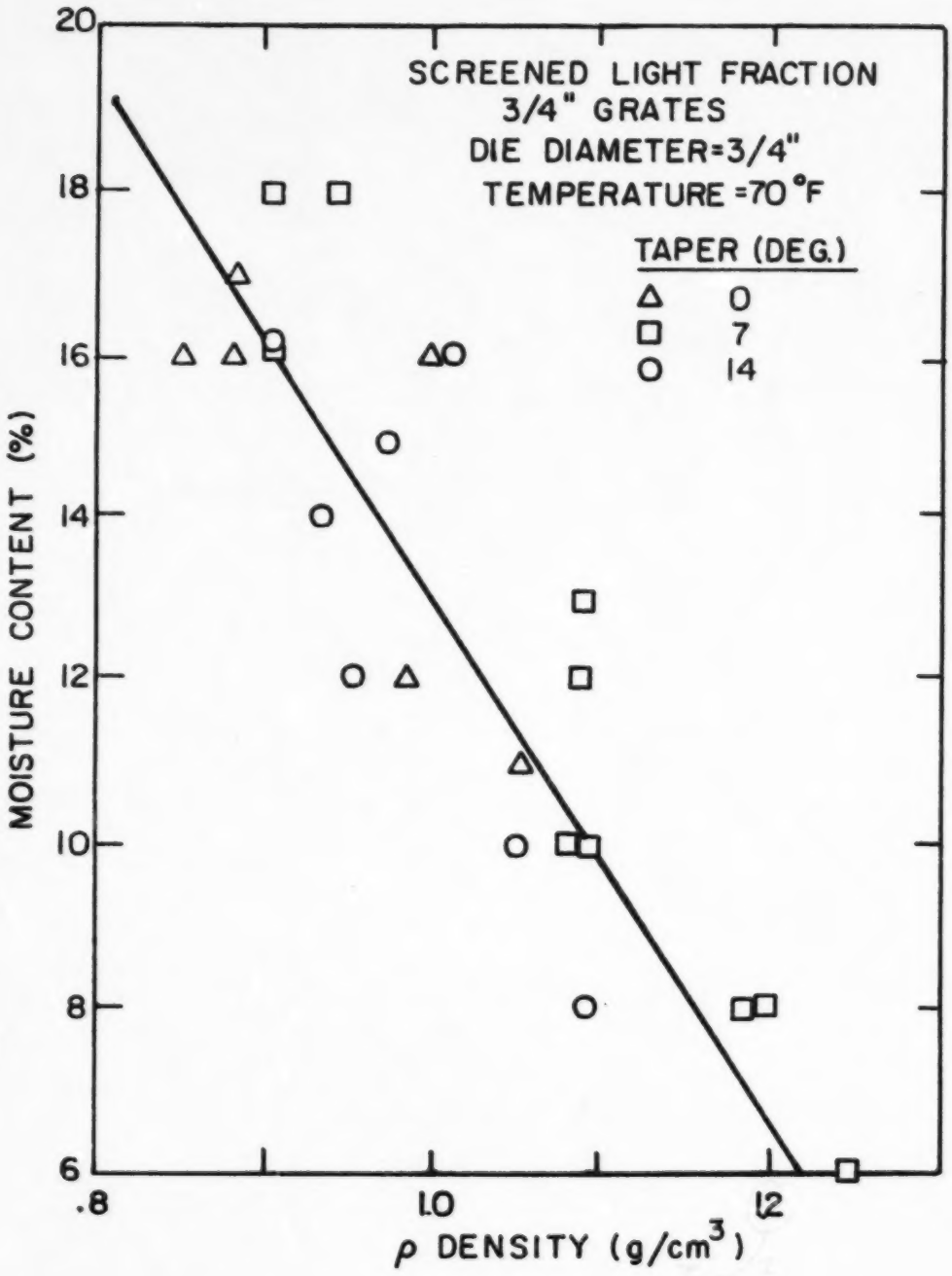


Figure 24 MOISTURE CONTENT VS. DENSITY

1/2 in. and extruded through dies of the diameters and tapers given in the table. The moisture content was held at 18 percent. The theory discussed previously predicts an effective yield stress, which is given by:

$$Y = \frac{P_D}{\ln A/a} \qquad (9)$$

For a given material, moisture content, and die taper, Y should be constant. However, according to the data in Table 3, Y varies from 2900 to 4840 psi for 0° taper dies, and from 2680 to 3910 for 14° taper dies. This conflict with theory is due either to a weakness in the theory, or to an excessive scatter in experimental results that may have been brought about by the use of a non-homogeneous (i.e. heterogeneous) material.

The data in the table does show that $P_D$ drops significantly with increase in diameter. This trend is predicted by equation 1 and is plotted in Figure 25.

TABLE 3. YIELD STRESS OF DENSIFIED RDF

| Die Diameter | Taper | Deformation Pressure (Psi) | ln A/a | Yield Stress (Psi) |
|---|---|---|---|---|
| 1/2 inch | 0° | 5280 | 1.39 | 3810 |
| 1/2 inch | 14° | 4380 | 1.39 | 3160 |
| 5/8 inch | 0° | 4550 | 0.94 | 4840 |
| 5/8 inch | 14° | 3680 | 0.94 | 3910 |
| 3/4 inch | 0° | 1670 | 0.58 | 2900 |
| 3/4 inch | 14° | 1540 | 0.58 | 2680 |

SPECIFIC ENERGY REQUIREMENTS OF PELLET FORMATION

The laboratory studies provided an opportunity to determine the ideal specific energy requirements of pellet formation by applying equation 3 or 4, or by deriving the pressure of extrusion directly from the force-deflection output charts. Specific energy is given by:

$$E_n = \frac{W}{m} = \frac{P}{\rho} = \frac{F/A}{\rho} \qquad (10)$$

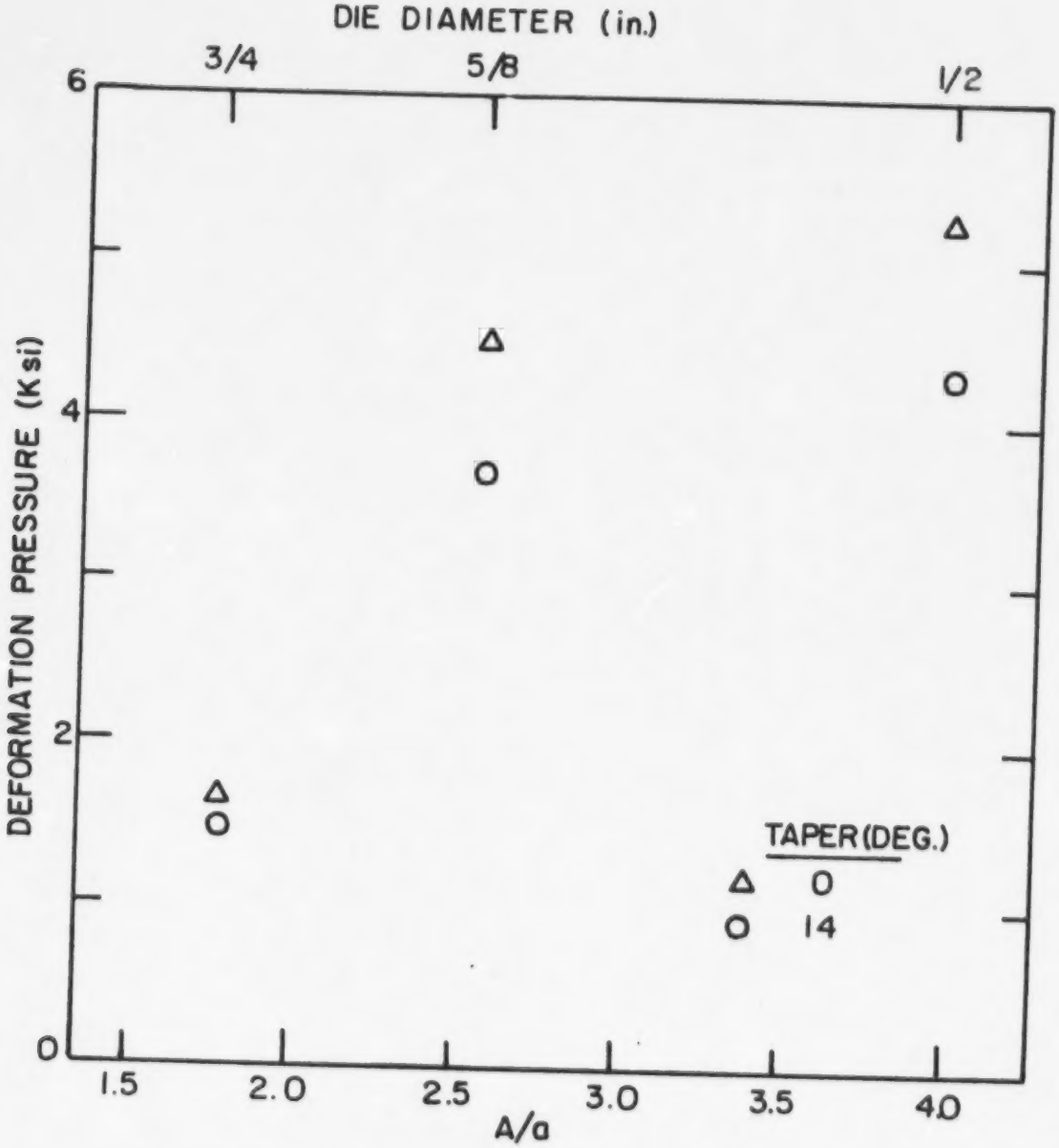


Figure 25 DEFORMATION PRESSURE VS. AREA REDUCTION RATIO

where $E_n$ = specific energy
$W$ = work
$m$ = mass
$P$ = pressure
$\rho$ = pellet density
$F$ = extrusion force
$A$ = pellet cross sectional area

The typical extrusion force to form a pellet 3/4 in. in diameter and having a 15 percent moisture content and a density of 0.9 g/cm$^3$ was found to be 3000 lb. Thus,

$$E_n = \frac{3000}{(\pi/4)\ (0.75)^2(0.9)} \quad \frac{lb/in^2}{g/cm^3} = 14.4 \ \frac{KWh}{Mt} \qquad (11)$$

## Section 5

## CONCLUSIONS

The following conclusions can be drawn from the basis of the results of the pellet mill tests:

1) The specific net energy of pelletization can be related to mass throughput by the equation

$$E_n = a\dot{M}_D^{\,b}$$

where a and b depend on die and feed characteristics.

2) Over a throughput range of 0.05 to 1.3 metric tons per hour the specific energy requirements decrease from 180 to 8 kWh/metric ton.

3) The maximum throughput capacity of the pellet mill (rated at 2 MTPH) for a characteristic feed size of 1.0 cm is 0.8 MTPH. The capacity decreases almost linearly to a value of 0.35 MTPH for 2.0 cm feed.

4) With pellets formed of screened light fraction material that has been passed through a shredder equipped with grates having 1/2-in. openings, and then densified in a 1/2 in. x 4 in. die, the density of the pellets falls from 1.31 to 1.12 g/cc as the moisture content is increased from 13.6 percent to 26.4 percent.

Trends exhibited in the single die studies must be considered in light of the basic differences between the procedure used and a full scale densification process. With this caveat, the following conclusions can be drawn:

1) Energy is required in the pelletization process to accomplish three distinct functions: precompression of the loose feed, deformation of the feed as it enters the die, and balancing of the die frictional force as the pellet passes through the die.

2) The frictional force can be related to die length and diameter by the equation

$$F = F_o \exp\left(\frac{4\mu L}{D}\right)$$

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3) Static friction necessitates the application of a greater force to begin the flow of a pellet than is needed to maintain the flow. Thus, stopping and starting the flow results in an increase in energy requirements.

4) The force required for deformation rises dramatically when the thickness of feed above the die inlet is less than one-half of the die diameter. This phenomenon may be attributed to changes in the orientation of material flow lines, and it might significantly contribute to the wear encountered in a commercial pellet mill, as well as to the energy requirements.

5) Although the pressure required for pellet deformation increases with extent of deformation, the classical model for homogenous crystaline materials,

$$P_D = Y \ln (A/a)$$

does not consistently and accurately predict the magnitude of this pressure.

6) A one percent increase in the moisture content of the feed decreases the deformation pressure by approximately 300 psi. However, if the moisture content exceeds 20 percent, a very weak pellet is formed.

7) Increasing the proportion of newsprint in the feed is accompanied by a dramatic rise in pressure.

8) Variations in feed and die temperatures apparently exert no effect on extrusion pressures.

9) Pellets formed by a die having an inlet taper of 14° consistently have a higher quality and a lower deformation pressure than do those formed by dies having a 0°, 2°, or 7° taper.

10) Typically, the specific energy consumed in deformation and friction at a moisture content of 15 percent is 14.4 kWh/MT.

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